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AVRADCOM Report No. 78-29

Production Engineering Measures Program
Manufacturing Methods and Technology

COMPUTER-AIDED DESIGN AND MANUFACTURING FOR EXTRUSION OF ALUMINUM, TITANIUM AND STEEL STRUCTURAL PARTS

PHASE II - APPLICATION TO PRACTICAL EXTRUSIONS

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January 1978

AMMRC TR 78-26

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Prepared for
U.S. ARMY AVIATION RESEARCH AND DEVELOPMENT COMMAND
St. Louis, Missouri 63166

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

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The overall objective of this program was to develop practical computer-aided design and manufacturing (CAD/CAM) techniques for extrusion of aluminum alloys, steels, and titanium alloys.

This program was conducted in two phases. This report covers the Phase-II work, which was completed by performing the following major tasks: (a) assemble geometric modules to represent practical extursion shapes, (b) apply the CAD/CAM method to a streamlined die, (c) develop a CAD/CAM system

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ABSTRACT

for non-lubricated extrusion through flat-face dies, (d) conduct extrusion trials and evaluate CAD/CAM extrusion.

In order to enhance readability, the results of Phase-II work are presented in the form of two volumes. Volume I includes the following chapters: (1) CAD/CAM of Streamlined Dies for Lubricated Extrusion of "T" Sections, (2) CAD/CAM of Flat-Face Dies for Nonlubricated Extrusion of Aluminum Structural Shapes, and (3) Extrusion of "T" Sections of Aluminum, Titanium and Steel using computer-aided techniques. Volume II is the Instruction Manual and describes the content and use of computer programs.

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FOREWORD

This final report on "Computer-Aided Design and Manufacturing for Extrusion of Aluminum, Titanium, and Steel Structural Parts - Phase II - Application of CAD/CAM to Practical Extrusions" covers the work performed under Contract DAAG46-75-C-0054, with Battelle's Columbus Laboratories, from July 19, 1976 to October 18, 1977.

The project was sponsored by the U.S. Army Aviation R & D Command, St. Louis, Mo. and contracted by the Army Materials and Mechanics Research Center, Watertown, Massachusetts. The U. S. AAVRADCOM project engineer was Mr. G. Gorline. The technical supervision of this work was under Mr. Roger Gagne of AMMRC.

This project has been conducted as part of the U.S. Army Aviation Manufacturing Methods and Technology Program, which has as its objective the timely establishment of manufacturing processes, techniques, or equipment to ensure the efficient production of current and future defense programs.

This program has been conducted in the Metalworking Section of Battelle's Columbus Laboratories, with Mr. T. G. Byrer, Section Manager. The principal investigators of the program are Dr. Vijay Nagpal, Research Scientist, Mr. Carl F. Billhardt, Staff Scientist, and Dr. Taylan Altan, Research Leader. Dr. Nuri Akgerman has been consulted throughout the program and contributed significantly to the quality of CAD/CAM programming effort.

In this phase of the program, a number of companies assisted Battelle in the development of CAD/CAM techniques through useful critique and discussions. The authors would like to acknowledge the assistance they received, especially from Mr. Mel F. Henley of Martin Marietta, Mr. C. O. Stockdale of ALCOA, Dr. R. J. Livak and Mr. F. S. McKeown of Consolidated Aluminum, and Mr. Jack Hockema of Kaiser.

PROGRAM SUMMARY

The overall objective of this manufacturing-technology program was to develop practical computer-aided design and manufacturing (CAD/CAM) techniques for extrusion of aluminum alloys, steels, and titanium alloys. It is expected that the application of CAD/CAM in extrusion will expand the capabilities of the extrusion process and reduce the cost of extruding and finishing structural components used in manufacturing military aircraft.

The Phase-II work, reported here, was largely devoted to develop the CAD/CAM method for extruding structural shapes from aluminum alloys through flat-face dies. The results, reported here, indicate that the objectives of Phase-II work have been fully achieved.

The success of any manufacturing-development program depends mainly upon two factors:

(1) The technical quality and the usefulness of the development work

(2) The acceptance, the application, and the use of the results developed in the program by the industry and others active in that field.

Therefore, in addition to fulfilling the technical requirements of the work, initial contacts were made with companies extruding aluminum, steel, and titanium alloys, in order to emphasize the practical and industrial aspects of these program results.

Introduction of CAD/CAM in Extrusion

Large numbers of extruded aluminum, titanium and steel components are used in the manufacture and assembly of military hardware. Most of these components are extruded by conventional hot extrusion techniques. Although the extrusion process has been a viable manufacturing process for many years, with the exception of glass lubrication in high-temperature extrusion, hardly any improvements have been made. Extrusion technology is still based largely upon empirical cut-and-try methods which result in the high cost of extruded products. Most of the tool design and manufacturing work for extrusion is still done by the intuitive and empirical methods. Therefore, extrusion die design and manufacturing is still considered an art rather than a science. In this respect, the state of the art in the extrusion technology is very similar to that of other metal-forming processes. The scientific and engineering methods, successfully used in other engineering disciplines, have not been utilized in extrusion. This situation can be explained by the inherent complexity of the extrusion process. The difficult-to-predict metal flow, the simultaneous heat generation and transfer which takes place during the process, the friction at the material-tool interfaces, and the metallurgical variations, make the extrusion process difficult to analyze from an engineering point of view. However, recently, computer-aided techniques for analyzing and simulating metal flow and deformation mechanics have been developed and proven. The application of these techniques along with advanced numerical machining (NC) allows the practical use of CAD/CAM in extrusion technology.

Program Approach

The Phase-II work included the following major tasks:

(1) Assemble geometric modules to represent practical extrusion shapes.
(2) Apply the CAD/CAM method to a streamlined die.
(3) Develop a CAD/CAM system for nonlubricated extrusion through flat-face dies.
(4) Conduct extrusion trials and evaluate CAD/CAM extrusion results.
(5) Evaluate the economics of CAD/CAM in extrusion.

Outline of the Final Report (Phase II)

Following the major steps identified in program approach, this final report is presented in two volumes. The first volume describes the technical work and is organized in three chapters:

- Chapter 1: CAD/CAM of Streamlined Dies for Lubricated Extrusion of "T" Sections
- Chapter 2: CAD/CAM of Flat-Face Dies for Nonlubricated Extrusion of Aluminum Structural Shapes
- Chapter 3: Extrusion of "T" Sections of Aluminum, Titanium and Steel using Computer-Aided Techniques

Volume 2 is the Instruction Manual and describes the content and the use of the system of computer programs ALEXTR. ALEXTR is the CAD/CAM system developed for nonlubricated extrusion of aluminum structural shapes.

In Volume 1, each chapter can be read separately, without having to go through the entire report to find information related to any of the major tasks conducted in this program. Thus, the use and the readability of this volume of the final report is enhanced.

Chapter 1 of Volume 1 of this final report describes the application of computer-aided manufacturing (CAM) and numerical control (NC) machining techniques to the manufacture of dies for extruding shapes such as L's and T's. To illustrate the application, lubricated extrusion of "T" shape was considered. Wood models of the EDM electrode for manufacturing the streamlined dies were machined by NC techniques developed in this phase of the work.

Chapter 2 of Volume 1 describes the work conducted towards applying CAD/CAM techniques to the nonlubricated extrusion of structural shapes of high-strength aluminum alloys. A system of programs called "ALEXTR" was developed for designing flat-face dies for extruding aluminum structural shapes, and for manufacturing the flat-face dies via numerical control (NC) machining techniques.

Chapter 3 of Volume 1 describes the extrusion trials conducted to evaluate the CAD/CAM techniques developed in this program. "Tee" sections of aluminum alloy Al 7075, titanium alloy Ti-6Al-4V, and AISI 4340 were extruded using flat-face and streamlined dies designed and manufactured using "ALEXTR" and "SHAPE" systems of computer programs. The results show the validity of CAD/CAM techniques developed under this program.

Volume 2 is the User's Manual which describes the use of "ALEXTR" system of computer programs for designing and manufacturing flat-face dies.

RESULTS OF PHASE-II EFFORT

The overall objective of this program was to develop practical computer-aided design and manufacturing (CAD/CAM) techniques for extrusion of aluminum alloys, steels and titanium alloys. The objective was completed by the Phase-II effort which utilized, as foundation, the work done in Phase I. Two interactive CAD/CAM systems, namely, "SHAPE" and "ALEXTR", have been developed. "SHAPE" system of computer programs allows CAD/CAM of streamlined dies for lubricated extrusion process which includes extrusion of steel and titanium alloys. "ALEXTR" computer system allows CAD/CAM of flat-face dies for the nonlubricated extrusion of aluminum alloys.

Phase II results can be summarized as follows:

- The computer-aided manufacturing and NC techniques developed in Phase I were extended to make "SHAPE" computer system applicable to extrusion of structural shapes, such as L's and T's.
- "ALEXTR" computer system for nonlubricated extrusion of aluminum alloys was developed.
- An economical-technical evaluation of the usefulness of CAD/CAM system in extrusion was performed. This study showed that utilization of CAD/CAM systems developed in this program can reduce manufacturing costs, improve delivery schedules, and increase the productivity of extrusion operations.

VOLUME 1

(6)

COMPUTER-AIDED DESIGN AND MANUFACTURING FOR EXTRUSION OF ALUMINUM, TITANIUM AND STEEL STRUCTURAL PARTS. PHASE-II - APPLICATION TO PRACTICAL EXTRUSIONS.

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CHAPTER 1

CAD/CAM OF STREAMLINED DIES FOR LUBRICATED EXTRUSION OF "T" SECTIONS

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CHAPTER 1

CAD/CAM OF STREAMLINED DIES FOR LUBRICATED EXTRUSION OF "T" SECTIONS

ABSTRACT

This chapter describes the application of computer-aided manufacturing (CAM) and numerical control (NC) machining techniques to the manufacture of dies for extruding shapes such as L's and T's. To illustrate the application, a "T" shape has been considered. The "streamlined" die surface for lubricated extrusion of a "T" shape from a round billet has been designed using the numerical techniques developed in Phase I of this program. To manufacture this die with a complex three-dimensional geometry, it is necessary to use the Electro-Discharge Machining (EDM) process. The EDM electrode is fabricated by NC machining. For this purpose, a numerical method has been developed and incorporated into the computer programs, SHAPE, written in Phase I of this project.

In order to provide completeness, this chapter summarizes both (a) the computer-aided die design techniques developed earlier in this program, and (b) the computer-aided manufacturing method completed as part of the Phase-II work.

INTRODUCTION

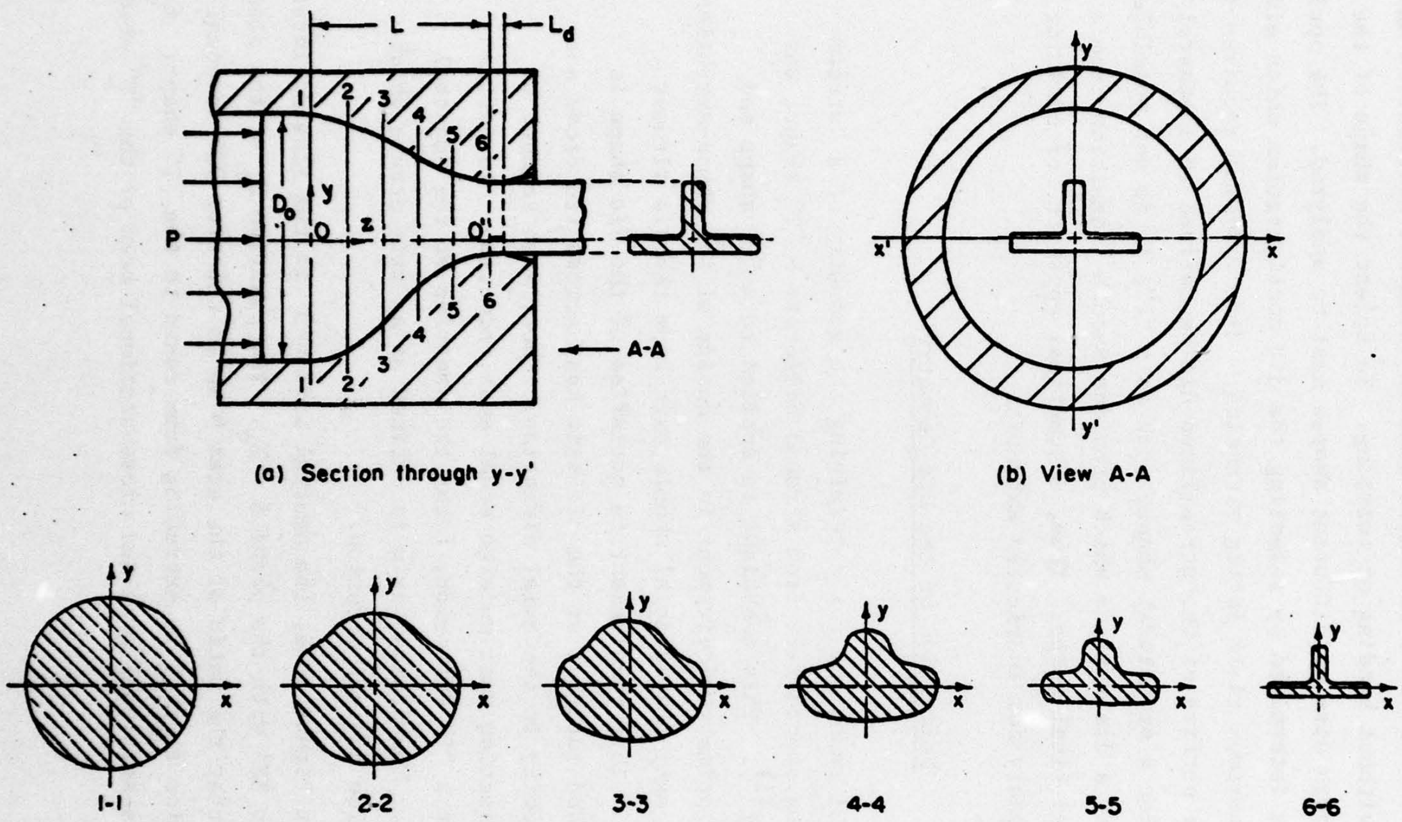
Large numbers of extruded aluminum, titanium, and steel components are used in the manufacture and assembly of military hardware. Most of these components are extruded by conventional hot extrusion techniques. Although the extrusion process has been a viable manufacturing process for generations, with the exception of glass lubrication in high-temperature extrusion, hardly any improvements have been made. Extrusion technology is still based largely upon empirical cut-and-try methods which result in the high cost of extruded products. Most of the tool design and manufacturing work for extrusion is still done by intuitive and empirical methods.

Aluminum alloys are extruded without using any lubricant through flat-faced dies. In extruding titanium alloys, steels and superalloys, various types of graphite and glass-base lubricants are used. The dies generally used in lubricated extrusion have a radiused die entry with a small lead in angle. The design and manufacture of these dies can be optimized by the computer-aided design and manufacturing (CAD/CAM) techniques developed in this program.

Phase I provided for the development of CAD/CAM techniques for extruding a modular shape of rectangular cross section using lubricated streamlined dies. These results were reported in the Phase I final report[1]. In the present Phase II work, these CAD/CAM techniques have been extended to handle the lubricated extrusion of "T and other similar sections using streamlined dies. The development of these techniques are discussed in this chapter.

COMPUTER-AIDED DESIGN (CAD) OF DIES FOR EXTRUDING "T" SECTIONS

The design of a "streamlined" die for extruding a "T" shape from a round billet is schematically illustrated in Figure 1-1. The geometry of this die and the variables of the extrusion process should be optimized to (a) give a defect-free extrusion requiring minimum post-extrusion operations (twisting and straightening), (b) require minimum load and energy, and (c) yield maximum throughput at minimum cost.



(a) Section through y-y'

(b) View A-A

(c) Cross Sections of the Billet During Extrusion

FIGURE 1-1. SCHEMATIC OF A STREAMLINED DIE FOR EXTRUDING A "T" SHAPE

In lubricated extrusion, the die should provide a smooth transition from the circular billet to the final extruded shape. In addition, the die surface should be such that the material undergoes minimum redundant deformation and also exits from the die without bending or twisting. To select the shape of the optimal die, metal flow through dies of different shapes must be analyzed. The optimal die geometry can then be determined by selecting the die configuration which gives the minimum energy and maximum yield during extrusion. This approach requires that, as a first step, the surface of the streamlined die be defined in a general and arbitrary manner. For a structural shape, such as a "T", it is not possible to describe analytically a die surface which provides smooth transition from a round billet to the desired final shape. Thus, a numerical approach for defining the die surface is necessary for lubricated extrusion.

Definition of the Die Geometry

A numerical technique for determining the geometry of a "streamlined" die, providing smooth flow from a round billet to a "T" shape, was developed in Phase I[1]. This technique is applied to a "T" shape and summarized here. A primary requirement in the design of the shape-extrusion process is that the extruded material should exit from the die without twisting or bending. This requirement is satisfied if the die shape is such that the extruded material at the die exit has, across its cross section, a uniform velocity in the axial direction. Thus, each segment of the original cross section must undergo equal area reduction. To define the die geometry for a "T" extrusion, first the position of the "neutral axis" is determined. The neutral axis is defined as an axis across which there is no metal flow during extrusion.

As seen in Figure 1-2a, the neutral axis 0-0' is the line of intersection of plane of symmetry XX' with the plane $X = X_c$. The position X_c of the plane $X = X_c$ is determined such that the ratio of the area 0'ab to the area 012 is equal to the overall area reduction (A_o/A_f) in extruding from round to the "T" shape. A_o and A_f are the billet cross-sectional area and cross-sectional area of the "T" product, respectively.

The initially circular cross section of the billet is then divided into a number of sectors, as shown in Figure 1-2b. Starting from a plane of symmetry, the final cross section is divided into the same number of segments. This is done while keeping the extrusion ratios (area of a sector in the billet/area of the corresponding segment in the product) equal to the overall extrusion ratio. Thus,

$$\frac{\text{Area } 012}{\text{Area } 01'2'} = \frac{\text{Area } 023}{\text{Area } 02'3'} \cdot \cdot \cdot \cdot \cdot \cdot \cdot = \frac{\text{Area } 056}{\text{Area } 05'6'} = \frac{A_o}{A_f} \; . \qquad (1\text{-}1)$$

According to this construction, the material points at positions 1, 2, 3, 4, 5 and 6 on the boundary B_o of the initial cross section move during extrusion to positions 1', 2', 3', 4', 5' and 6', respectively, on the boundary B_f of the final cross section. Thus, the initial and final positions of the material flow lines along the die surface are determined. The path followed by any material point between the initial and final positions is not known. Therefore, arbitrary curves are fitted between corresponding points of the boundaries B_o and B_f. These curves define numerically a general die surface, any portion of which can be changed by adjusting the curves fitted in that portion of the surface.

The procedure outlined above is used to write a system of computer programs called "SHAPE". The basic structure of "SHAPE" is described in the Final Report on Phase I[1]. Figure 1-3 shows a plot of the streamlined die surface generated from "SHAPE" for extrusion of a "T" section. Due to symmetry, only the upper half of the die surface is plotted.

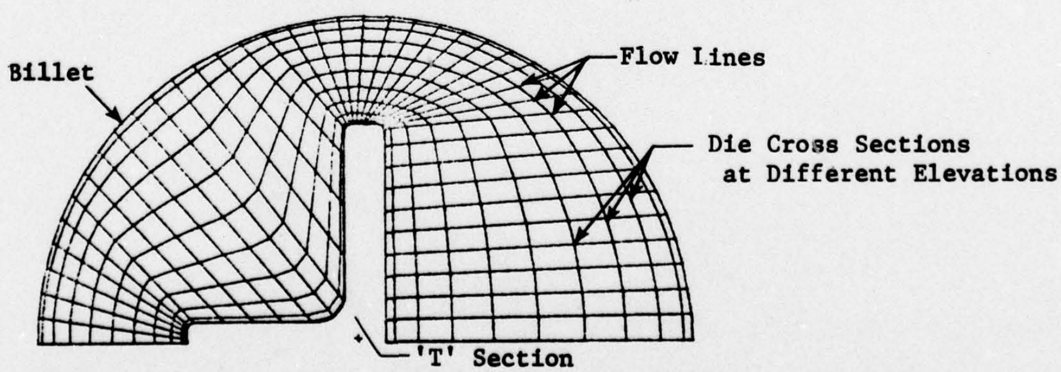


FIGURE 1-3. A STREAMLINED DIE SURFACE FOR EXTRUDING A "T" SHAPE FROM A CIRCULAR BILLET

Calculation of Extrusion Load and Die Pressure

The total extrusion pressure P_{avg} is given as the sum of its components by:

$$P_{avg} = P_{fc} + P_{id} + P_{sh} + P_{fd} + P_{fl} , \qquad (1\text{-}2)$$

where P_{fc} = component of pressure due to friction in container

P_{id} = component of pressure due to internal plastic deformation for area reduction

P_{sh} = component of pressure due to shear deformation at entrance and exit of the die

P_{fd} = component of pressure due to friction at die surface

P_{fl} = component of pressure due to friction at die land.

The details of the analysis are given in Reference(1). Essentially, the mean-extrusion pressure and the distribution of pressure on the dies are obtained as a function of the process variables, such as initial billet diameter, initial billet length, speed of the extrusion press, final extrusion shape, area reduction, type of die, friction at container and die surfaces, temperature, and flow properties of the material being extruded. For given values of these process variables, the extrusion load is calculated numerically. Special computer programs, developed for this purpose, form "SHAPE".

Optimization of the Die Design

The die design (configuration of the die surface and the die length) is optimized with respect to the load required to extrude a particular shape. The extrusion pressure is calculated numerically for different die lengths and the die length corresponding to the minimum extrusion pressure is selected. Regarding the die profile, the analysis for extrusion of an elliptic shape showed that (a) minimum extrusion pressure is required when smooth polynomial curves are fitted between the boundaries of the billet and the extrusion, and (b) the pressure is not very sensitive to the shape of the polynomial curve[1]. Based on this information, the program "SHAPE" uses polynomial curves, fitted between the billet and product (extrusion) boundaries.

COMPUTER-AIDED MANUFACTURING (CAM) OF EXTRUSION DIES

The surface of a "streamlined" die is defined as an array of points, as seen in Figure 1-3 for a "T" shape. The practical method of manufacturing this die is to NC machine a carbon electrode and then to EDM the die. In Phase I of this project, computer programs were developed to generate NC tapes for manufacturing streamlined extrusion dies. These programs successfully generated dies for round, elliptic, and rectangular sections. However, they were not applied to more complex sections, such as a "T" section, containing concave (fillet) radii. The problem with fillet radii lies not in the analysis or design of the die surface, but rather it occurs when one attempts to generate the offset cutter paths necessary for NC machining the desired surface. At fillets, the potential exists to generate gouging cuts when the cutter offset is developed. This undercutting problem and the steps taken to eliminate it are discussed below.

In the process of adding new portions to the program system "SHAPE", the entire program structure was revised in order to utilize new versions of system utilities (FORTRAN compiler and segmentation loader) on the CDC 6400 computer. The resultant program structure is described in Appendix A. The new program segments, which were added to the system, are documented in Appendix B. Appendix C defines the FORTRAN Named Common segments used to transfer data between the program segments.

Calculation of Cutter Paths

To machine a part using a numerically-controlled (NC) machine tool, it is necessary to calculate a cutter path offset from the desired shape. This is because the cutting tool is positioned based on the center of the tool, while the material removal takes place at the surface of the cutter. The difference between the center point of the tool and the cutting point is the tool radius. The motion of the tool center forms a path all around the part to be cut. For three-dimensional shapes, the tool path can be thought of as a second surface, parallel at all points to the surface to be machined.

A potential problem exists in developing the offset path wherever a concave (fillet) radius is encountered. If the tool radius is smaller than or equal to the concave radius, there is no problem. However, if the tool is larger than the surface radius, the desired radius cannot be cut. Furthermore, it is likely that attempting to make a cut under such conditions will result in gouging, or undercutting the surface. The condition of a tool radius larger than a concave and convex surface radius is shown in Figure 1-4, for the simple two-dimensional case. The cutter offset path for the convex (corner) radius can be generated for any cutter size, and this path will accurately generate the desired surface. At the concave (fillet) radius, however, the best that can be expected is that the cutter will leave an uncut cusp.

If the part surface is identified as a series of points defining the vertices of a polygon (again considering the two-dimensional case), with a radius of appropriate sign at each point, analytical techniques can be developed to examine the surface. Such procedures will determine the offset at each vertex, and will generate the proper offset so as not to undercut the surface. If, however, the surface is defined, not as a polygon, but simply as a series of points randomly spaced along the surface, such analytic techniques cannot be used. In this case, the cutter centerline is determined by finding normals to the part surface at each point and then offsetting along the normal a distance equal to the cutter radius. This causes no problems along linear or convex portions of the surface. At a concave portion, however, the cutter will gouge the surface, unless steps are taken to prevent this from happening. Gouging occurs because the cutter offset is determined with respect to a point on the part surface without regard to the position of the cutter with respect to the rest of the part surface.

For shaped extrusion dies, the surface contours in the X-Y plane are defined as polygons at only two locations: the entry and exit. This is illustrated in Figure 1-5 where the coordinate axes are shown. The entry to the die is a circle and, therefore, totally convex. Thus, the offset can be found using normals to the surface, and no possibility of gouging exists. At the exit, the contour is defined as a polygon of the vertex points with associated radii. Techniques can be developed to inspect the surface and prevent undercuts. For contours between the entry and the exit, however, the contours are known only as points on the part surface. This is because these intermediate contours are generated based on a mathematical function defining the contour of the material flow paths between the two known contours.

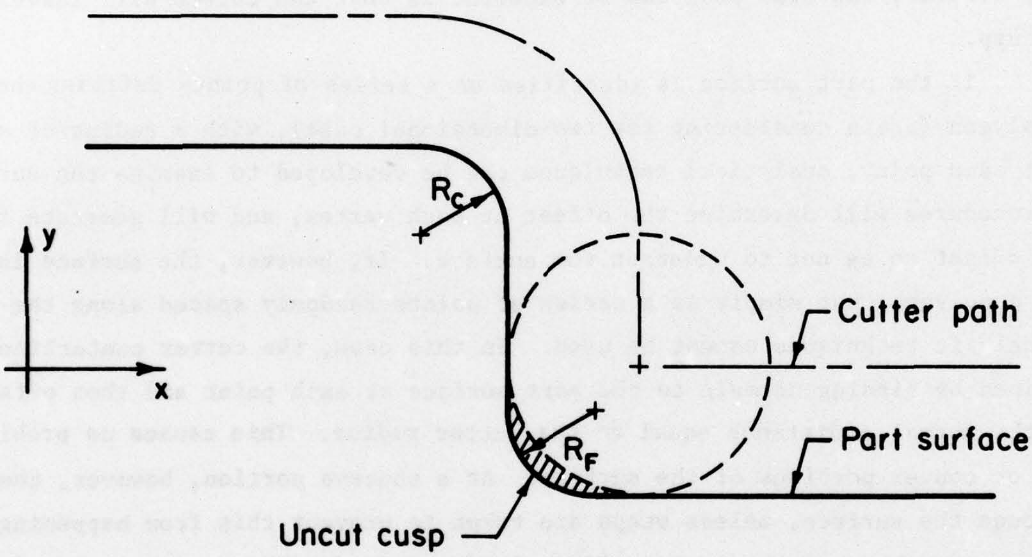


FIGURE 1-4. CUTTER PATH GEOMETRY AT A CORNER AND A FILLET IN TWO-DIMENSIONAL NC MACHINING

The potential for gouging exists at any concave point, both in X-Y contours at constant elevation, and along a flow path in X,Y,Z space.

Checking and Prevention of Gouging

To determine whether a calculated tool offset path will gouge the surface, two techniques were considered. The first one is called the patch test. In this, the distance from the cutter center to a series of points on the part surface is calculated. The points on the surface define a patch. Some number, N, of points on either side of the cutter along two axes, for example Z and X, defines the patch. Thus, the total number of distances calculated for each cutter offset point is $4N^2$. The major problem with this is the number of calculations necessary. To check with any degree of certainty, N should be at least 4 or 5. For these values, 64 to 100 calculations are required. If, as is done in the second technique, checking is only done in the X-Y plane, 8 to 10 calculations are necessary at each point. A further complication with the patch test is that if a gouge condition is found, how is the gouge to be removed other than be restarting with a smaller cutter.

The technique which was adopted was to convert the cutter offset points on a given X-Y plane from X-Y space to R-θ space. The polar coordinates R (radius) and θ (angle) are calculated relative to the center of the extruded part, not the center of the billet. The part center lies on the "neutral" axis, obtained during the design of the die geometry, as seen in Figure 1-2a. Therefore, the part center does not necessarily coincide with the billet center. θ is calculated in a counter-clockwise fashion from 0 to 2π, as seen in Figure 1-5. Adjacent θ values are then compared with each other. No undercut or gouge will exist if θ continually increases. When a condition is found that

$$\theta_{N+1} < \theta_N \quad , \tag{1-3}$$

an undercut exists. Plotted in R-θ space, an undercut would appear as a loop, somewhat similar to a cardioid curve (seen in Figure B-1 in Appendix B). A technique has been developed to determine which offset points will cause gouging and to replace these with non-gouging points. A description of this technique is given in Appendix B.

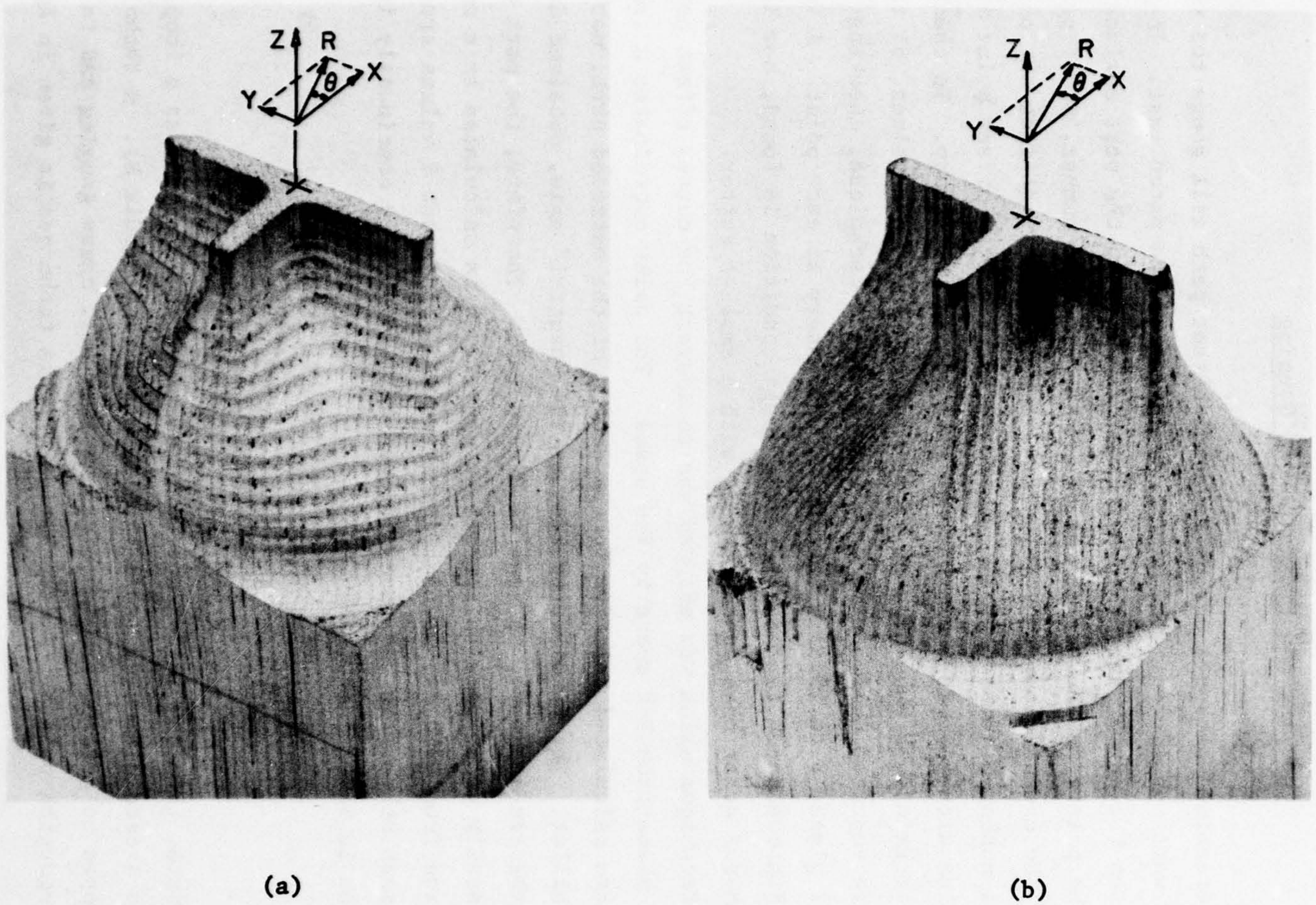


FIGURE 1-5. NC MACHINED WOOD MODELS OF EDM ELECTRODES

a. Machined along section planes
b. Machined along flow lines

Two assumptions or caveats must be considered as part of the R-θ search technique. These are:

(1) The technique is applicable only to sections which have a center from which lines can be drawn to any point on the surface without intersecting any other point on the surface. Shapes which can be treated include angles, tees, and crosses. Channels, zees, H's, etc., cannot be processed by this algorithm.

(2) The technique assumes undercuts potentially exist only in X-Y planes. Each plane is examined for undercuts independent of any other plane. This assumption is felt to be valid, considering the various designs encountered, and the relative transition length to billet diameter ratios of the dies.

MACHINING MODELS OF EDM ELECTRODES

Figures 1-5a and 1-5b show wood models of EDM electrodes made using the NC machining techniques, described above. In actual practice, such electrodes would be cut in graphite and then hand polished.

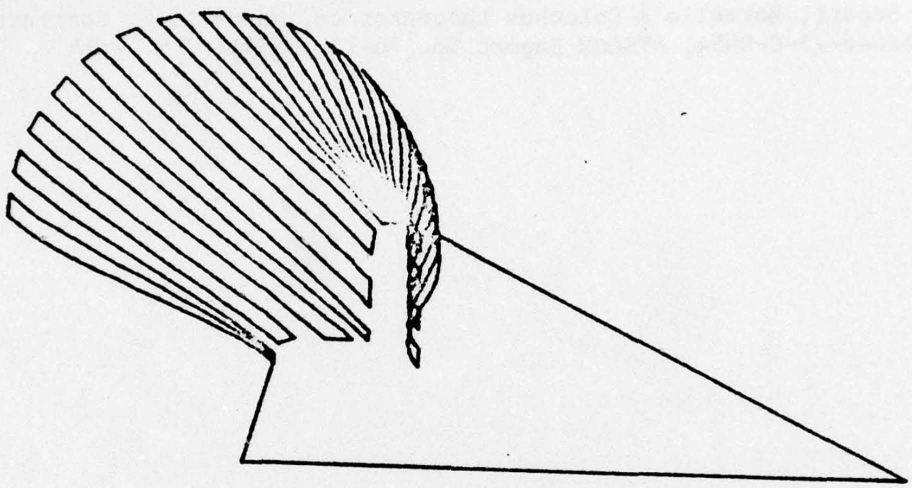
The model in Figure 1-5a was cut as a series of contour planes, each plane being at essentially the same elevation. The cutting paths are the same as those used in the R-θ analysis for undercuts. The problem with cutting in this manner is that a relatively rough surface results because of the large spacing between each plane. The number of planes could have been increased, but at a very high cost for the increase in computer memory required.

An analysis was made to evaluate the path length of the cutter when machining along planes, Figure 1-5a, and machining along streamlines. It should be noted that, due to the part being symmetrical about the X-axis, only half the part was defined. The mirror image feature of the Computer Numerical Control System, used at Battelle for NC machining was then applied to the other half. The perimeter of half of the shape is approximately 3 inches; the perimeter of half the billet is about 5 inches. Using the average, or 4 inches, with 16 planes, results in a total path of 64 inches. Along the 91 flow lines, the average length is about 2 inches for a total length of 183 inches. Thus, machining along the flow lines gives almost a three times longer cutter path than machining along the planes. This increase in cutter path length is available at no increase in the size of the data arrays used, or the amount of memory required. Because of the longer cutter path length, the model machined along the flow lines, Figure 1-5b, has a considerably smoother surface in the as-machined condition than does the model machined along the section planes.

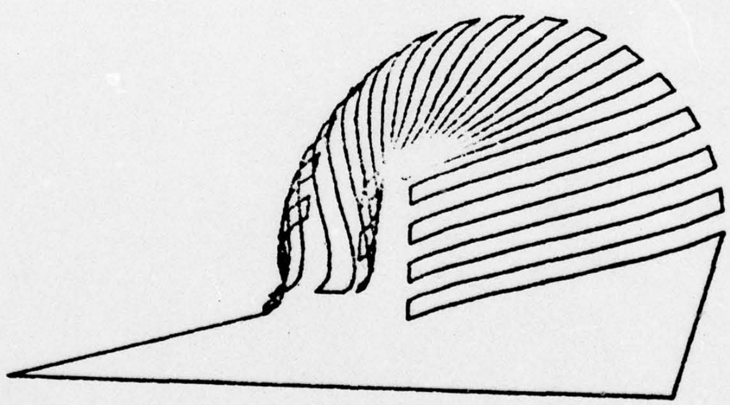
To machine the models, both roughing and finish cuts were used. After the cutter paths were calculated, they were plotted on the screen of a cathode ray tube (CRT) terminal so that large errors could be deducted prior to cutting the models. Figure 1-6 illustrates two isometric views of the cutter offset paths used for finish machining the model seen in Figure 1-5b. The roughing cut was made with a 1/2-inch ball-end mill. A series of passes were made with this cutter, with the first cut starting 2.5 inches above the block and the last cut starting 1.0 inch above the block. The system is programmed such that the final exit contour will be machined when the cutter is 1.0 inch above the surface. Two finish passes were then made with a 3/16-inch cutter with the final cut starting .75-inch above the center. This resulted in the surfaces shown in Figures 1-5a and 1-5b.

The 3/16-inch cutter used for the finish pass is equal to the concave radii on the Tee section. When this size cutter was used by the program, no indication was given by the program that gouging existed. As a general rule, it is felt that finish cuts should always be made with a cutter equal to or less than the smallest concave (fillet) radius defined on the finish section.

The results show that the gouge detection system implemented into SHAPE appears to yield good results. If any undercuts exist after being processed by the detection and removal algorithm, they are of such small size that they can be removed in the finish machining cuts with a small cutter. The surface finish was dramatically improved by machining along the flow lines, rather than along the section planes. This is because of the considerably longer cutter path which is generated along the flow lines, even though the amount of data is the same in both cases.



(a) 45 Degree Projection



(b) 135 Degree Projection

FIGURE 1-6. CRT DISPLAY OF CUTTER OFFSET PATHS

REFERENCES

(1) Nagpal, V., and Altan, T., "Computer-Aided Design and Manufacturing for Extrusion of Aluminum, Titanium and Steel Structural Parts (Phase I)", Final Report, Battelle's Columbus Laboratories, March 1976, Contract No. DAAG46-75-C-0054, AVSCOM Report No. 76-12. (AMMRC CTR 76-6).

APPENDIX A

PROGRAM STRUCTURE

APPENDIX A

PROGRAM STRUCTURE

While the undercut checking programs were added to SHAPE, the entire program system was changed from an overlay structure using RUN Fortran to a segment loaded structure using FTN Fortran. This was done because FTN is a newer version of Fortran, and RUN is no longer supported. The segment loader allows greater flexibility than overlays in structuring a system of programs. With overlays, the overlay segments and relationships to one another must be declared at compile time. With the segment loader, the individual segments are compiled as separate pieces, irrespective of their relationship to one another. The program structure is created by means of directives to the segment loader at the time the absolute load image file is generated. This structure can be modified by changing the segmentation directives and recreating the load file, without having to update and recompile the source program elements.

The structure of the program system is shown in Figure A-1. In this form, the system required 53416 (octal) words of memory to run. This included an error recovery package which was used for debugging. If the error recovery package was deleted, the system would probably run in less than 50,000 words.

The segment which governs the size of the program system is DIENC. The major cause is the large arrays needed to contain the cutter offset data. This uses three sets of 16 x 92 words each for a total of 4416 (decimal) words. The segmentation of DIENC has been made as fine as possible. The other major segments, DIESH and ANALY, could be segmented finer but this would serve no purpose unless DIENC was reduced in size.

A number of files are used for input and output. These are defined as follows:

(1) TAPE1: An output file used for intermediate results, and debugging messages.

(2) TAPE2: An input file containing the coordinates of the polygon defining the desired extrusion. This file must be ATTACH'ed before the program is executed.

(3) TAPE3: An output file used for the NC machining data. If a tape is to be punched, this file should be sent to the

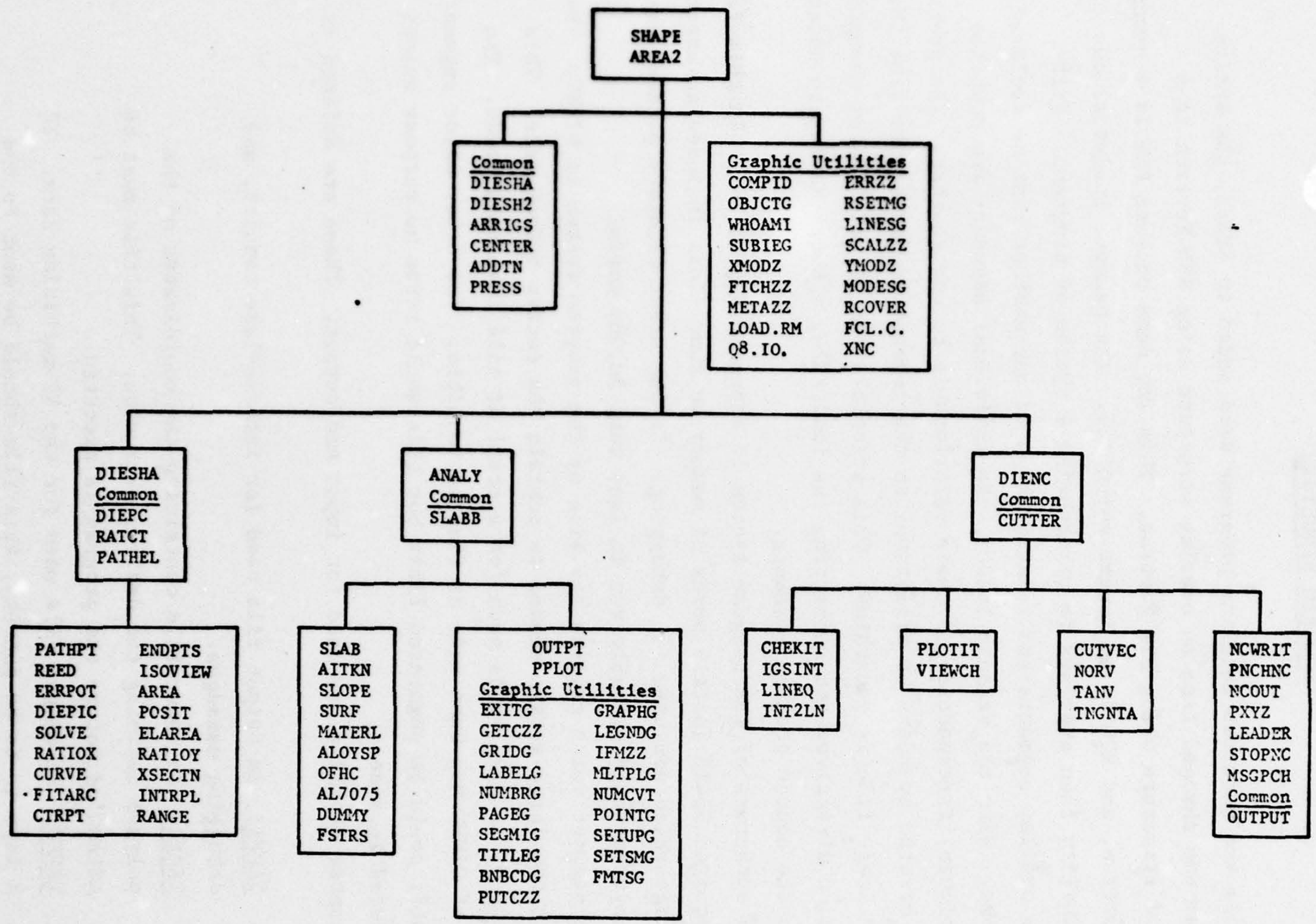


FIGURE A-1. STRUCTURE OF PROGRAM SYSTEM SHAPE USING SEGMENTATION LOADER paper tape punch by means of the ROUTE directive.

(4) TAPE5: Used for input from the terminal.

(5) TAPE6: Used for output to the terminal.

APPENDIX B

DESCRIPTION OF SUBROUTINES

APPENDIX B

DESCRIPTION OF SUBROUTINES

Subroutine CHEKIT (KERR, RT, BATCH)

Subroutine CHEKIT is used to check for undercuts in the cutter paths calculated to generate the die EDM electrode. It does this by examining the cutter offset points calculated for each elevation in Z. That is, the cutter offsets are calculated as a series of points X(I,J), Y(I,J), Z(I,J) where I is the index to the Z elevation plane, and J is the index to the radial division. The points are calculated by finding each X, Y, Z for each elevation for one radial division at a time. The result is that the cutter offsets for each radial division are related to each other along a division. However, each radial path is calculated independent of any other radial path. CHEKIT operates by examining the relationship of each radial point on an elevation to other points on the same elevation, essentially acting as though each elevation is independent of any other elevation.

To do this, CHEKIT transforms the cutter offset data for each plane to polar coordinates, by calculating R and θ for each point relative to the center of the shape. This center may or may not be the geometric center of the billet. When R and θ have been found, a loop is then started to check that

$$\theta_{I+1} \geq \theta_I \quad . \tag{B-1}$$

If this is the case, no action is taken. If Equation (B-1) does not hold, a condition similar to that shown in Figure B-1 exists. In this case, $\theta_5 < \theta_4$. Point 4 is called the first reversal point. A search is then started to find where θ again reverses. In Figure B-1, 8 is the second reversal point.

To be on the safe side, the indices to the reversal points are expanded by two before testing that the reversal points are satisfactory boundaries for the undercut. That is, the left boundary is set to 2 (4-2), and the right boundary is to 10 (8 + 2). A test is then made to determine if θ_{BL} (left boundary) is greater than θ_{BR}. In Figure B-1, θ_{10} is less than θ_2 and the preliminary bounds are not satisfactory. Which one to change is determined by testing the radius associated with each boundary. The index to the boundary with the smaller radius is modified as appropriate. In this case, $R_{10} < R_2$, so the index to θ_{BR} is advanced such that $\theta_{BR} = \theta_{11}$. The angles of the boundary points are again compared, and the above process repeated until $\theta_{BR} > \theta_{BL}$. In this case, $\theta_{11} > \theta_2$.

The point associated with each boundary, going in the direction of the undercut, is then used to find the intersection. In this case, points (2,3) and (10,11) define two line segments in R,θ space. Subroutine LINEQ is used to find the equation of each segment and INT2LN is used to find the intersection point. The intersection point is then tested to determine that

$$\theta_X > \theta_{LB},\ \theta_X < \theta_{RB} \quad . \tag{B-2}$$

If either or both of these conditions is not met, the index to the appropriate bound is incremented (θ_{RB}) or decremented (θ_{LB}) as many times as is necessary to obtain these inequalities. In the case shown, no modification is needed since both bounds satisfy the inequalities on the first try.

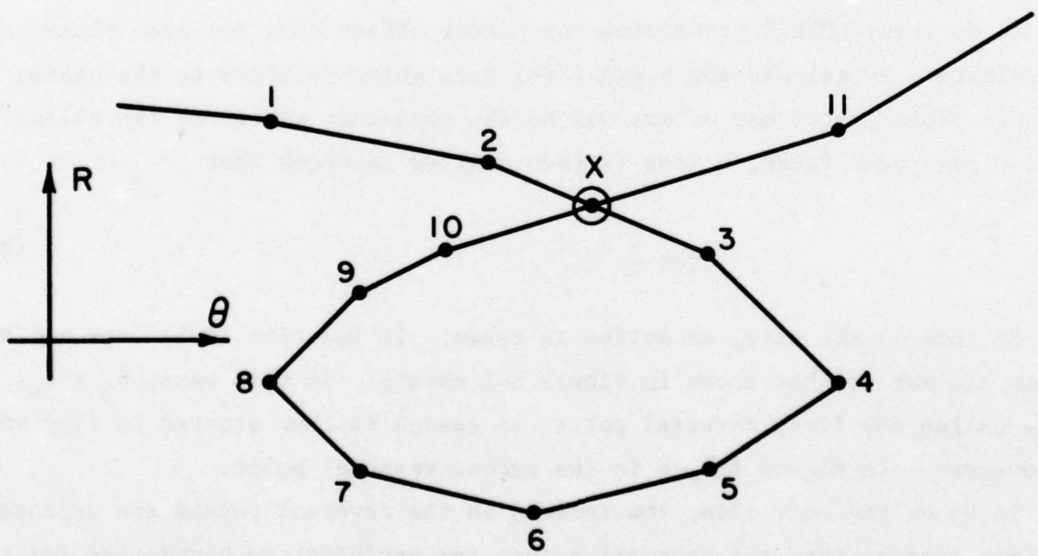


FIGURE B-1. GEOMETRY OF CUTTER UNDERCUT IN R-θ SPACE

The X,Y and Z averages of the resultant boundary points are then determined. These averages are substituted for the associated X,Y and Z values of the points which lie between the boundaries. That is, for the X axis

$$\bar{X} = (X_2 + X_{11})/2$$

$$\text{and} \qquad X_3, X_4, X_5 \ldots X_{10} = \bar{X} . \qquad \text{(B-3)}$$

The average of the two boundaries is used to replace the points between the boundaries so that each plane will have the same number of coordinates. This is necessary because machining is done by moving along the radial patterns. That is, the cutter is moved to the Ith point on each plane, starting from Plane 1 and going to Plane N. When the cutter reaches Point I of Plane N, it moves to Point I+1 on Plane N. The cutter is then moved to adjacent I+1 points from the inside to the outside.

After an undercut is located and handled, as described above, the search algorithm continues from θ_{RB} to determine if any other undercuts exist along the plane. Further undercuts, whether on the same or other planes, are treated as described above. When all planes have been searched, CHEKIT returns to DIENC.

The very first time an undercut is located, the user is given the opportunity to choose a smaller cutter. If he elects this option, he is asked to enter the new cutter radius. CHEKIT then returns to DIENC with the new cutter size and KERR = 2. DIENC will then loop back and calculate the cutter offset positions based on the original part coordinates. If the program is running in BATCH mode, when an undercut is found, CHEKIT will remove the points causing the undercut.

Figure B-2 illustrates a cutter undercut situation in X-Y, Cartesian space. The offset required for a cutting tool is found by determining the normal to the surface at each point on the surface, and then moving the cutter radius away from the surface along the normal. This is done without "looking ahead" to examine where all points on the cutter surface lie.

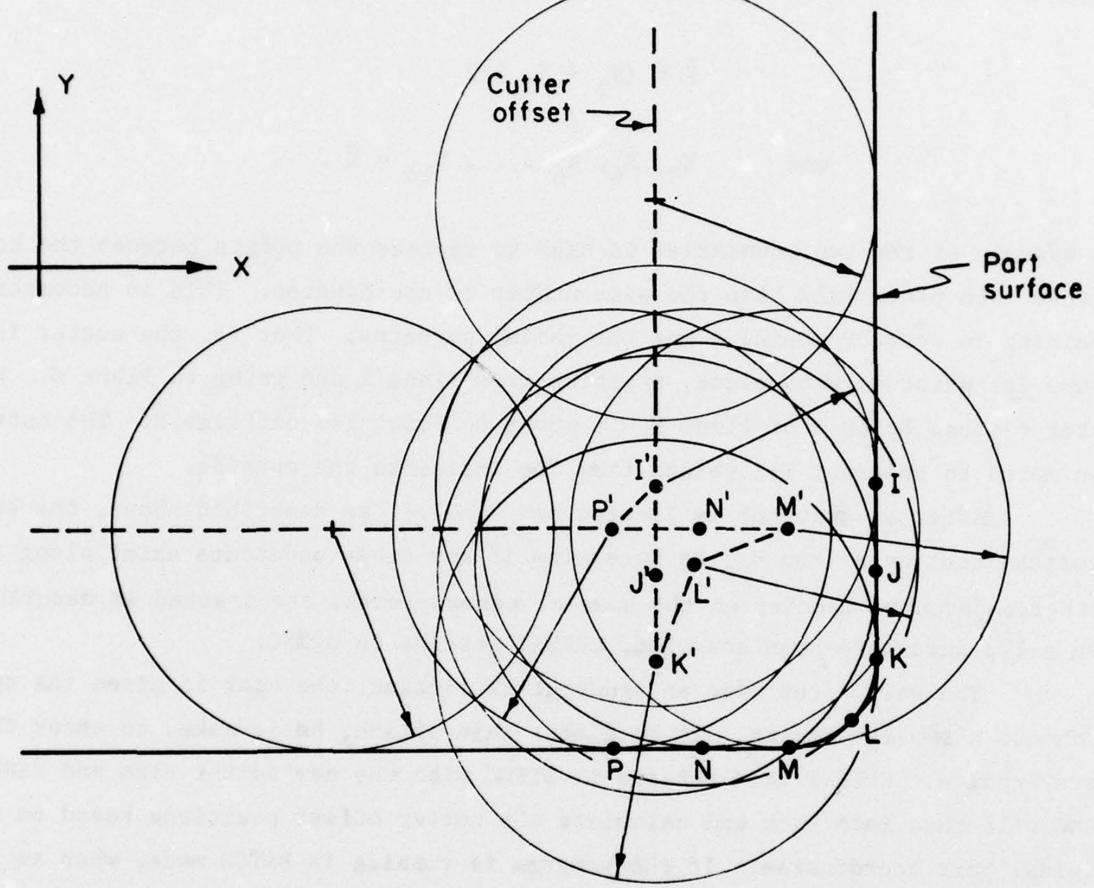


FIGURE B-2. GEOMETRY OF CUTTER UNDERCUT IN X-Y SPACE

Program DIENC

DIENC is the root segment of the third group of overlays. Its purpose is to call subroutines which generate the cutter offsets needed to machine the electrode for the die defined in overlays 1 and 2. It starts by incrementing the number of axial (planes) and the number of radial (segments on a plane) divisions into which the part is to be divided for cutter offset calculations. This ensures the shape is completed properly.

The initial location for the cutter is specified to be directly above the center of the billet. The height is specified as one inch plus the tool radius. The first move is sideways along the + X axis to a distance of the billet radius plus two inches. The third move will then take the cutter on a tapered path to the billet radius along + X at the depth specified for the overall die length. A double DO loop is then started to find the cutter offsets. This finds the cutter positions for each elevation along each radial path. Subroutine CUTVEC is used to find the components of the cutter radius along each axis. These components are added to the point on the surface of the part to determine the location of the cutter. When all cutter center-line points on the part have been determined, the tool is retracted vertically away from the part, and then moved back to the origin.

Subroutine CHEKIT is called to check for undercuts. This subroutine gives the user the opportunity to specify a smaller cutter size if an undercut is found. If the user elects this option, the entire procedure for finding the offsets is repeated with the new cutter size. If in interactive mode, the cutter paths are then plotted on the CRT in isometric projection using subroutine PLOTIT. The user may specify different viewing angles to see the cutter paths from different orientations. Figure 1-6a is the cutter path for half of a "T" shape as originally plotted. Figure 1-6b is the same cutter path redrawn at an angle of 135 degrees from the X-Y plane, rotating about the Y axis. The final function of DIENC is to produce an NC tape, if this option has been specified. This is done by subroutine NCWRIT.

Subroutine INT2LN (E1, E2, X, Y)

Given the coefficients for two lines, this subroutine finds the intersections of the two lines. The coefficients are passed via the three element arrays E1 and E2. The point of intersection is returned as X and Y.

Subroutine LEADER(N)

LEADER uses NCOUT to output leader code to the output file. N frames of leader code are generated. LEADER is called from NCWRIT, after the title is punched, at the completion of each radial machining pass, and at the end of NCWRIT just before the NC file is closed. The ASCII code for leader is equivalent to a line feed (12_8).

Subroutine LINEQ (X1, Y1, X2, Y2, COEF)

Given the coordinates of two points, X1, Y1 and X2, Y2, LINEQ determines the coefficients of the straight-line defined by the points. The coefficients are those for the general form of the equation of a straight-line which is A*X + B*Y = C. A, B, C are returned as the elements of the three element array, COEF.

Subroutine NCOUT(IC,ID)

This subroutine stores all characters which are to be output to the NC tape file in a buffer. When the buffer is full, or when otherwise directed, the buffer is copied to a file. The character being output (IC) is stored in a buffer. When the buffer is full (128 characters), the buffer is copied to the output file and then cleared. The buffer will be copied before it is full if parameter ID is set not equal to one.

Subroutine NCWRIT(RT)

NCWRIT is used to generate a file of the cutter coordinates in either ASCII or EIA format. Normally, this file would be directed to the paper tape punch to produce the tape which is then run on the NC machine. After initializing various constants and tables, subroutine MSGPCH is called to generate a message at the beginning of the tape. This message gives the size of the cutter (RT) to be used when machining with the tape.

A double DO-loop is then started to output the cutter coordinates to the tape file. This is done in a similar fashion to that used in PLOTIT. That is, odd-numbered passes are output in direct order (outside to inside), while even-numbered passes are output in reverse order (indise to outside). Five frames of leader are generated at the end of each pass. After all passes and the return moves to the starting location are output, the NC stop code is generated. This is followed by a final 10 frames of leader.

NCWRIT is the last function called by DIENC. When NCWRIT is completed and control is returned to DIENC, DIENC then returns to the master root segment, SHAPEX.

Subroutine PLOTIT(THETA,AL)

PLOTIT plots a cutter centerline path on the CRT as an isometric projection. The viewing point is changed by specifying the angle, θ, that the part is rotated about the Y axis, at a point half way through the depth of the piece, AL. The (X,Y,Z) cutter coordinates are transformed to the (XP,YP) CRT display coordinates using the following functions:

$$XP = X + (Z - AL/2) \cos(\theta) \qquad \text{(B-4)}$$

$$YP = Y + (Z - AL/2) \sin(\theta) \ . \qquad \text{(B-5)}$$

To limit the amount of memory required, the plot coordinates for a single radial path are calculated and displayed before calculating the next radial path. The odd-numbered paths (1,3,5 . . ., 2 N+1) are plotted from the outside (round billet) to the inside (final shape); the even-numbered paths go from inside to outside. To allow the points to be plotted in the correct sequence, the transforms for points on even-numbered passes are made in the reverse order for which they are to be plotted. A special index, JR, is used to keep track of whether the pass is odd or even. This is initially set to 1. It is then reserved at the end of each pass so that the following holds:

JR Value	Meaning
1	Odd-number pass
-1	Even-number pass

When all surface coordinates are plotted, the final moves to return the tool to the starting point are found and displayed. PLOTIT then returns to DIENC.

Figure 1-6a is an example of the output of PLOTIT. This was made at an angle of 45 degrees, which is the default value passed to PLOTIT the first time it is used.

Subroutine PNCHNC(X,Y,Z,M)

PNCHNC formats absolute coordinate data into the incremental form required for the BCL CNC milling machine. To do this, it first converts the absolute value to an integer representing the size of the move in thousandths of an inch. That is, for an X-axis move

$$IX = \text{integer part } (1000 * X) \ . \qquad \text{(B-6)}$$

This integer, absolute value, is then converted to integer incremental form by subtracting the current value from the previous value as follows:

$$IDX = IX_{new} - IX_{old} \ . \qquad \text{(B-7)}$$

The old integer value is then replaced by the new integer value, and subroutine PXYZ is called to output the current move. When m = -1, the initial "old" values for the three axis are set, but no data is output.

After each set of X,Y,Z coordinates is processed, an end-of-block mark (i.e., carriage return, line feed) is appended to the output file using NCOUT.

To summarize the operation of the NC formating routines, assume the following three(3) sets of absolute coordinates exist:

X	Y	Z
1.154	2.837	0.549
1.289	2.956	0.650
1.508	3.254	1.064

The two vectors represented by these values would appear in the output file as:

X135	Y119	Z101	(first vector)
X219	Y298	Z414	(second vector)

It should be noted that PNCHNC contains data tables for preparing tape in either EIA or ASCII format. By "Commenting" the one table not desired, either format can be produced.

The variables in the calling sequence are as follows:

X,Y,Z: Arrays of absolute coordinates in user units

M: The number of elements in each of the above arrays.

Subroutine PXYZ(INC,NAME)

PXYZ takes the integer data representing incremental motion commands for any of the three axes, converts the data to individual ASCII or EIA characters, and then uses NCOUT to output the characters. The routine operates by repeatedly dividing the input value, INC, by successively smaller powers of 10. The quotient, if not a leading zero, is output via NCOUT. The quotient is next multiplied by the same power of 10 and subtracted from the initial value to get the next value.

For example, let INC = 1234. Since the largest move possible on the BCL CNC milling machine is about 36 inches (36,000 moves of 0.001 inches each), the first power of 10 is 10^4 or 10,000. Thus, the first digit to be output is:

$$INT = \text{integer}\ (1234/10000) = 0 \quad . \qquad (B-8)$$

$$\begin{aligned} INC_{New} &= INC_{Old} - INT * 10000 \\ &= 1234 - 0 * 10000 \\ &= 1234 \quad . \end{aligned} \qquad (B-9)$$

On the next pass, the power of 10 is reduced to 10^3 or 1000. Then,

$$INT = \text{integer}\ (1234/1000) = 1 \ . \qquad (B-10)$$

The ASCII representation of 1 (61_8) is sent to the output file and the new value becomes:

$$\begin{aligned} INC &= 1234 - 1 * 1000 \\ &= 234 \quad . \end{aligned} \qquad (B-11)$$

This process repeats until all digits have been processed.

The variables in the calling sequence are as follows:

INC: The integer value for the distance to be moved along the axis NAME

NAME: The ASCII code for the axis along which a move of INC size is to be made.

Subroutine STOPNC

STOPNC causes an "MØØ" code to be punched on the NC output tape file. This code indicates a program stop to NC controllers. STOPNC is called at the end of NCWRIT after all coordinate data has been output.

Subroutine VIEWCH(THETA,ANS)

Subroutine VIEWCH is called by DIENC after PLOTIT, to allow the user to specify other viewing angles to PLOTIT. It first asks the user if the viewing angle is to be changed. If the response is other than Y (Yes), a return is made to DIENC. If the response is Y, the user is then asked to enter the viewing angle, THETA, desired using namelist VIEW. The user is expected to enter the angle in units of degrees. VIEWCH converts THETA to radians before returning to DIENC. When control is returned to DIENC, the value of ANS is examined. If it is Y, DIENC loops and calls PLOTIT again, giving it the specified value for THETA.

APPENDIX C

COMMON BLOCKS

APPENDIX C

COMMON BLOCKS

The following defines the major common blocks as they are used in the DIENC segment of SHAPE.

COMMON / DIESHA /

1. XP(50), YP(50) - Coordinates of the polygon defining the extrusion (input)
2. XX(16,92), YY(16,92), ZZ(16) - Coordinates on die surface for each flow path. This permits 92 streamlines with 16 points on each streamline to be defined.
3. AL - Length of the die, inches.
4. DEBUG - If .TRUE., prints details to aid in debugging (.FALSE.)
5. ANGLIM - Angle defining the portion of the die to be analyzed, degree.
6. DETAIL - If .TRUE., prints intermediate results on TAPE1 (.FALSE.)
7. TAPE - If .TRUE., cutter coordinates are stored on TAPE3 (.TRUE.)
8. RT - Radius of ball-end mill, inches.
9. RAD - Radius of the billet, inches.
10. BATCH - If .TRUE., program runs in batch mode.
11. CHKINT - Spare logical variable.
12. NSKIP - Number of sets of data to be skipped before reading the desired set (Ø).
13. MANUAL - If .TRUE., coordinate data is entered from the keyboard (.FALSE.)
14. ISOMET - If .TRUE. and BATCH = .FALSE., isometric view of die surface is plotted.
15. LO - Initial length of the billet.
16. LD - Die-land length, inches.
17. MC - Friction shear factor at material-container interface.
18. MD - Friction shear factor at material die interface (0.3)
19. VO - Ram speed, inches/minute (20.)
20. TEMP - Initial billet temperature, F. (800.)

21. NIP - Number of data points input to define the shape of the extrusion.

22. XN(4), YN(4) - Array used by subroutine CTRPT to find the neutral axis.

23. IS - Index of the starting point for area calculation in subroutines RATIOX and RATIOY

24. IL - Index of the last point for area calculation in subroutines RATIOX and RATIOY.

COMMON / ADDTN /

1. IUNIT - Code to specify extrusion shape category:

   = 1; rectangle, Tee or similar shape having at least one plane of symmetry
   = 2; shapes with no plane of symmetry.

2. NAXIAL - Number of parts into which the die length is divided (10).

3. NDIV - The number of radial divisions into which the die surface is divided for the purpose of defining the die surface numerically.

4. NCURVE - Code to specify the type of curve fitted along the flow path lines

   = 1; polynomial
   = 2; straight-line.

5. IMATER - Code representing the material being extruded.

6. DETCTR - If .TRUE., the position of the neutral axis will be found (IUNIT must equal 1) . (.TRUE.)

7. OPTLEN - If .TRUE., the optimum length of the die is determined (.TRUE.)

8. ANALYS - If .TRUE., stress analysis is to be performed.

COMMON / CUTTER /

1. X(16,92), Y(16,92), Z(16,92) - Cutter centerline position coordinates. These coordinates define the path necessary to machine the part surface.

2. XC(4), YC(4), ZC(4) - The starting and ending cutter positions, before or after the actual surface machining is done. Note: XC(1) = XC(4), YC(1) = YC(4), ZC(1) = ZC(4).

3. NA - The number of axial parts into which the die length is divided, plus one (NA = NAXIAL + 1).

4. NR - The number of radial divisions into which the die surface is divided, plus one (NR = NDIV + 1).

COMMON/ DIESH2 / (As used by DIENC and CUTVEC)

1. RX(16), RY(16), RZ(16) - Relative offset of the cutter center from a surface point, for each point on a flow line.

2. AX(16), AY(16), AZ(16) - Components of the vectors tangent to each point on a flow line. These vectors lie in the plane of the flow line.

3. BX(16), BY(16) - Components of the vectors normal to each point on a flow line. These vectors lie on the cross section plane. If BZ were generated, the value would be zero for all points.

(As used by CHEKIT)

1. R(92), THETA(92) - The cutter offset coordinates for a plane, expressed in polar coordinates.

2. C1(3), C2(3) - Coefficients of line segments, generated by LINEQ and used by INT2LN.

(As used by PNCHNC and NCOUT)

1. IXO, IYO, IZO - The initial or previous position of the cutter.

2. IE - Unused.

3. NC - The number of characters currently stored in the NC output buffer.

4. NR - Unused.

5. NB - The size of the NC output buffer in words. This is the number of ASCII or EIA characters which the output buffer can contain.

6. LUNNCO - Unused.

7. IA(128) - The NC output buffer.

CHAPTER 2

COMPUTER AIDED DESIGN AND MANUFACTURING (CAD/CAM) OF FLAT-FACE DIES FOR NON-LUBRICATED EXTRUSION OF ALUMINUM STRUCTURAL SHAPES

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CHAPTER 2

COMPUTER-AIDED DESIGN AND MANUFACTURING (CAD/CAM) OF FLAT-FACE DIES FOR NON-LUBRICATED EXTRUSION OF ALUMINUM STRUCTURAL SHAPES

ABSTRACT

This chapter describes the work conducted towards applying CAD/CAM techniques to the extrusion of structural shapes of high-strength aluminum alloys. A computerized method has been developed (a) for designing flat-face dies for extruding aluminum structural shapes and (b) for manufacturing the flat-face dies via numerical control (NC) machining techniques. The computer-aided design and manufacturing (CAD/CAM) method, developed in this program has been incorporated in systems of computer programs called "ALEXTR" and "EXTCAM". These systems can be applied not only to structural shapes, but also to more complex sections. The validity of "ALEXTR" and "EXTCAM" was established by actual extrusion of "Tee" sections of Al 7075 using these CAD/CAM systems. Chapter 3 gives the results of the extrusion trials.

Volume 2 of the final report is the User's Manual for "ALEXTR" and "EXTCAM". This volume should be referred to for detailed description of the use and operation of these systems. This chapter provides an overview of these CAD/CAM systems with regard to their structure, capabilities and limitations. Also presented in this chapter is an economic-technical evaluation of "ALEXTR" and "EXTCAM". The results of this evaluation show that application of computer-aided techniques can reduce considerably manufacturing costs and delivery schedules and increase the productivity of the extrusion operations.

INTRODUCTION

The extrusion process for extruding soft aluminum alloys is well established. This is evidenced by the very large range of shapes being successfully extruded from soft alloys. Many years of experience lie behind the production of extrusion dies with increasing complexity of shape, thinness of section and quality of surface. Some of this experience is rationalized in empirical design rules, but much of die design is still dependent on personal judgment, intuition and experience. The dies are proven by trial extrusions. Invariably, the die orifice is corrected to achieve the required control of cross-sectional dimensions, straightness and surface quality.

For high-strength aluminum alloys (2000 and 7000 series), used in military applications, the variety of extruded shapes is relatively limited. With these alloys, the extrusion rates are low, the materials are expensive and the production costs are high. Optimization of process, process control and die design are, therefore, likely to have greater economic impact for extruding hard aluminum alloys.

In today's industrial practice, the design of the die configuration is an art rather than a science. Die design is developed from previous experience, costly sub-scale experimentation and in-plant trials. To reduce the costs of developing die designs and the costs of manufacturing the dies, automated computer-aided design systems for nonlubricated, as well as lubricated, extrusion are being developed[1,2].

The specific objectives of applying computer-aided design techniques to the hot extrusion of aluminum alloys are:

- Provide scientific basis and rationalize the die-design procedure, as much as possible.
- Improve productivity by reducing the trials and corrections needed to prove the dies.
- Optimize the die design to achieve optimum material yield and maximum productivity.
- Reduce the lead time required for designing and manufacturing the die.

- Reduce die manufacturing costs by using cost-effective numerical control machining techniques whenever appropriate.
- Optimize process variables to improve productivity and reduce cost.

DESIGN AND MANUFACTURE OF FLAT-FACE DIES

The four general types of dies used for extruding aluminum are: flat-face, porthole, bridge and baffle or feeder plate[3,4]. The dies primarily used for extruding structural shapes are flat-face dies. The design of this type of die is considered here.

The flat-face die is essentially a flat disc of tool steel containing one or more shaped orifices. The hot metal is forced to extrude through these orifices to give the desired sections, as shown in Figure 1. The detailed design of the die involves determination of the following:

- Optimum number of shaped orifices in the die
- Location of the orifices relative to the billet axis for uniform metal flow through each orifice
- Orientation of the orifices
- Modification of the shape of the orifices to correct for thermal shrinkage and die deflection under load
- Determination of bearing lengths for balancing metal flow.

Manufacturing the die by NC (Numerical Control) machining and EDM (Electro-Discharge Machining) techniques may require generation of an NC tape for machining the:

- Template of the finished extrusion
- Die opening
- Electrode for EDMing the openings
- Die land bearings into the back of the die

AUTOMATED DESIGN AND MANUFACTURE OF FLAT-FACE DIES BY COMPUTER

System Concepts

The procedure to design a flat-face die can be organized as a sequence of logical decisions. Each decision is affected by a multitude of interrelated factors. Considerable computation is involved if the optimum design is the goal. Thus, in the design process, the computer can be used to (1) assist the designer in studying the effect of various process variables so that he can choose the optimal solution, (2) perform routine computational work for the designer, and (3) make decisions, which are based on an established logic and which do not require perception.

Based on the above concept, two computer-aided design and manufacturing systems, called "ALEXTR and "EXTCAM" were developed. These systems are implemented on a minicomputer. The interaction between the computer and the designer is via interactive computer graphics. The major hardware components, shown in Figure 2, are:

- PDP-11 with 28K memory
- Disk drives
- VT11 display processor and graphics tube
- Keyboard terminal
- X-Y plotter

Program Approach

"ALEXTR" is a system of computer programs which are written to follow certain logical design procedures, as outlined in Figure 3. Computer programs are based on empirical and analytical relationships, as well as on established guide rules discussed in Volume 2 of this final report. "ALEXTR" was evaluated by conducting extrusion trials, described in Chapter 3 of this report.

The use of "ALEXTR" for designing extrusion dies starts with the description of the extrusion shape. The cross section of the extrusion is expressed in terms of x, y coordinates and the associated fillet or corner radii. Thus, cross-sectional data are input and "ALEXTR" uses these data to calculate geometric

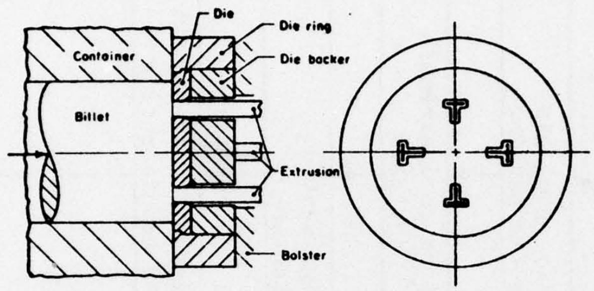

FIGURE 1. SCHEMATIC OF THE EXTRUSION OF STRUCTURAL SHAPES THROUGH A FLAT-FACE DIE

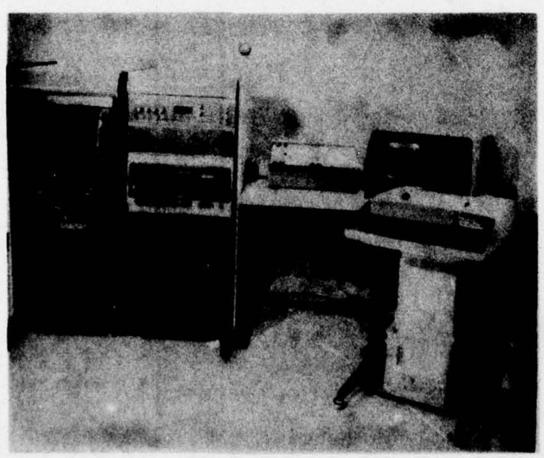

FIGURE 2. PDP-11/40 MINICOMPUTER SYSTEM WITH REFRESH GRAPHICS DISPLAY TERMINAL USED IN DEVELOPING THE SYSTEM OF COMPUTER PROGRAMS

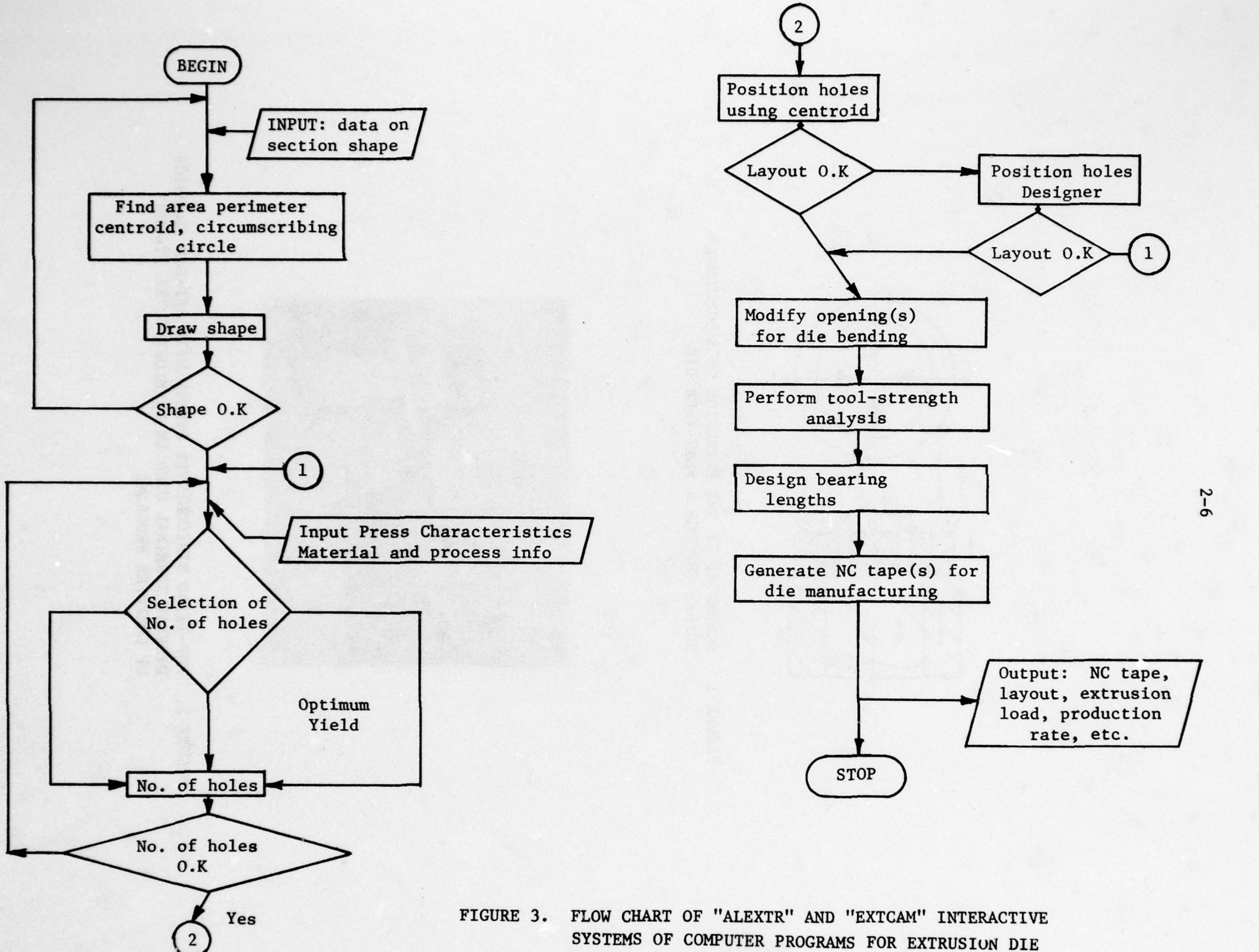

FIGURE 3. FLOW CHART OF "ALEXTR" AND "EXTCAM" INTERACTIVE SYSTEMS OF COMPUTER PROGRAMS FOR EXTRUSION DIE DESIGN AND MANUFACTURE

parameters such as cross-sectional area, perimeter, centroid and circumscribing circle. Also, the extrusion shape is plotted on CRT (Cathode Ray Tube) and on an x-y plotter.

For each available press, characteristics such as press capacity, container diameters, maximum billet length, runout length, etc., are stored in a data table. The designer specifies the particular press he intends to use and also inputs the information on process variables such as billet material and extrusion temperature. The number of holes is then determined, based on the particular technique selected by the designer.

If the optimum yield is used as the criterion, the number of holes for maximum recovery of billet material, as well as for maximum pounds per hour, are determined.

The next step in the design process is the layout of the hole(s). "ALEXTR" positions the holes using the centroid technique. That is, the CG (center of gravity) of the hole opening is placed to coincide with the CG of the billet segment feeding that opening. The opening is also rotated such that its greatest distance is parallel to and as close as possible to the chord of the segment. This layout can be modified by the designer if he wishes. If the designer is unable to layout the holes due to insufficient clearances, he can go back and select a different number of holes.

After the layout is complete, "ALEXTR" corrects the openings for die cave and die deflection. A tool-strength analysis is then performed to determine the bending and shear stresses in the die, backer and bolster due to the extrusion pressure. The need for conforming tools to support the die is also determined by the tool-strength analysis.

The next step in the design process is the determination of die bearings. The die bearing at any position is dependent upon the section thickness at that position and its distance from die center. The user (designer) specifies the applicable thickness which is used by "ALEXTR" to calculate the die-bearing length. The dimensions of the opening are expanded to compensate for thermal shrinkage and stretching.

"EXTCAM" takes the designed dimensions for the openings(s) and generates the cutter path NC tape used to manufacture the die. Tapes can be obtained from "EXTCAM" for (a) machining the template of the finished extrusion, (b) machining the die opening itself, (c) machining the EDM electrode or for (d) machining the die bearings from the back of the die. The size of the cutter to be used is specified by the user. The output from the computer includes the NC tape(s), a hard copy plot of die layout, and die design data such as dimensions of the openings, bearing lengths and pounds per hour, extrusion load, etc.

At various stages of the design, the perception of the designer is advantageously used to assist the computer. For example, the die layout determined by "ALEXTR" is easily checked visually by the designer when plotted on the CRT. Similarly, the tongues in the die can be much more easily located by the designer from the CRT display than by a computer program.

Use of the ALEXTR/EXTCAM Systems

A variety of sections were used to develop and verify the "ALEXTR" and "EXTCAM" systems of programs. A "T" section was, however, processed, extruded and manufactured using these systems. Chapter 3 gives the details of the design and manufacture of the die, and the results of the extrusions made using this die.

ECONOMIC-TECHNICAL EVALUATION

The overall objective of the CAD/CAM extrusion systems, developed in this program, is to reduce manufacturing costs and delivery schedules of extrusions and to increase the productivity of extrusion operations. The benefits of applying the CAD/CAM extrusion systems, in practical production conditions can be summarized as:

- Improve precision in cost estimating.
- Improve accuracy in die manufacture, thereby produce extrusions with closer dimensional tolerances.
- Provide a scientific basis for die design, thereby reduce die design costs and reduce costly die trials.

- Reduce requirements for skilled manpower.
- Reduce costs and lead times for die design and manufacture.
- Optimize extrusion process variables to improve productivity and to increase material utilization.

In order to evaluate these potential benefits, listed above, it is necessary to review the details of the present extrusion practice.

Present Extrusion Practice

The various steps involved in producing extruded products can be summarized as follows:

1.0 Estimating

1.1 Receive customer inquiry (section drawing, material specifications, quantity, delivery date).

1.2 Prepare Quotation.

1.2.1 Determine the circumscribing circle, the area, and the perimeter of the cross section.

1.2.2 Estimate die costs, including backup tooling.

1.2.3 Estimate press costs, including auxiliary equipment and handling.

1.2.4 Estimate material costs, including scrap losses.

2.0 Die Design and Manufacture

It is assumed that the order is received and the results of calculations, made in Step 1.2.1 above, are available. At this stage, a precise cost estimating and control system is necessary.

2.1 Determine the optimum number of orifices in the die, estimate the extrusion load, and select the appropriate extrusion press.

2.2 Locate and orient the orifices relative to billet axis for uniform metal flow and select the backup tooling, if it is available.

2.3 Correct the dimensions of the die orifices to account for thermal shrinkage and local die deflection.

2.4 Design die bearings to assure appropriate shape definition and straightness.

2.5 Prepare a die drawing.

2.6 Manufacture the die either by tracer copymilling or by EDM (wire or conventional).

3.0 <u>Determination of Process Conditions</u>

3.1 For the given press and number of die orifices, select optimum billet and butt lengths to give maximum yield.

3.2 Select billet temperature, uniform or variable in axial direction.

3.3 Select press speed for the given alloy to result in maximum production rate without extrusion defects (hot shortness in hard alloys).

4.0 <u>Extrusion, Straightening, Stretching</u>

4.1 Perform die trials and make corrections to ensure straightness and die fill.

4.2 Extrude.

4.3 Stretch, straighten and saw to appropriate lengths.

4.4 Package and ship.

Potential Non-Tangible Benefits of the CAD/CAM Extrusion Systems

The CAD/CAM systems developed in this program are only applicable to solid shape dies at this time, and cannot entirely handle porthole, bridge or feeder-plate type dies. Nevertheless, in the extrusion of solid shapes, especially those from hard alloys and for military applications, these systems would assist companies in a variety of ways to improve the efficiency of current operating practices. The CAD/CAM systems would be helpful in virtually all the various operational steps, discussed above. The major non-tangible benefits, which could be provided by the present CAD/CAM systems, are:

- <u>More Precise Estimating</u>. In order to be competitive, the quotes given to potential customers must reflect adequate costs and profit. Estimates on the high side result in loss of business, while those on the low side do not generate adequate profit and may even cause actual loss. The CAD/CAM systems would improve the accuracy of estimating, at no additional cost.
- <u>Reduction in Delivery Schedules</u>. The NC tapes for CAM of extrusion dies could be produced within a few hours of receiving the section design. Consequently, it would be possible, on receipt of the order, to manufacture the dies sooner than with conventional practices. This would markedly improve the competitiveness of a company.
- <u>Less Dependence upon Skilled Die Makers.</u> It is increasingly difficult to find skilled craftsmen with long experience, who can design and manufacture extrusion dies. The use of CAD/CAM would reduce this problem in the future and most dies could be designed and manufactured by less skilled operators.
- <u>Reduction in the Number of Die Failures.</u> With CAD, die stresses can be predicted more accurately. Thus, in marginal cases where dies are loaded to near their ultimate strength, more thorough die analysis would avoid die failures.
- <u>Improved Utilization of Existing Press Capacity.</u> Often, the load requirement for a given shape cannot be accurately estimated. Therefore, a press with a larger capacity than that absolutely necessary is used. In some extreme cases, an order is not accepted when an incorrect estimate indicates that the largest press in the plant cannot handle the job. More accurate load predictions would help to reduce these occurrences.
- <u>Continuous Improvement of Die and Process Technology.</u> The CAD/CAM systems can be continuously updated based on current experience in die design and optimum extrusion conditions. This experience would be "stored" in the computer system and would help to refine and improve the procedures for estimating die design and predicting optimum extrusion conditions.

Potential Tangible Benefits of the CAD/CAM Extrusion Systems

In order to identify and estimate the cost benefits which may result from the application of the CAD/CAM systems, it is helpful to consider (a) the common problem areas in extrusion which may be affected by the introduction of the CAD/CAM systems, and (b) a hypothetical extrusion plant where the system may be introduced.

Common Problem Areas in Extrusion Practice

An extensive evaluation of extrusion plant operations and costs is reviewed by Ferguson from Alcoa[5] and Waugh[6] of Kaiser. Based on this information, the common problem areas which can be affected by CAD/CAM application are:

(1) Extrusion Conditions and Operations

- Extruding at a slower speed than necessary reduces productivity.
- Using billets which are too short or too long reduces yield and productivity.
- Excessive breakthrough pressures, because the press capacity is barely sufficient for the job, requires slowing the press and lowering productivity.

(2) Dies

- Inadequate die bearing design causes excessive twist in the extrusion. As a result, scrap losses increase and/or handling requirements for stretching and twisting increase.
- In multiple-hole dies, inadequate die design causes variable runout lengths. If one or more sections are too short or too long, scrap losses increase.
- Unnecessarily long bearings and excessively large reduction ratio slow production.
- New dies requiring more than one trial waste valuable press time and increase scrap losses.
- Dies designed to give an extrusion within tolerances, but having dimensions on the heavier side, result in loss of material and reduce yield.

Specifications of an Extrusion Plant as an Illustrative Example

For the purpose of illustrating the potential cost benefits of CAD/CAM application, consider an extrusion plant as follows:

- Equipment: Four extrusion presses, 1000 to 5000 ton capacity.
- Plant Capacity Per Year: 48 million pounds gross (this value is estimated by considering that a 2500-ton press can process 12 million pounds of billets when operating five days/week and two 8-hour shifts/day[5].
- Cost Per Press Per Hour: $100 to $200, average $150.
- Equipment Utilization Rate: 60 percent (50 to 60 percent is considered average in the industry[5]).
- Material Utilization: Shipped product weight versus incoming billet weight is 75 percent. (This value varies between 70 to 80 percent[5]; 15 to 30 percent scrap is due to (a) butt length, (b) lengths of extrusion on both ends, used for stretching and twisting, and (c) scrap due to high twist, unequal runout length in multiple-hole dies, or insufficient die fill).
- New Dies Per Year: 1000 (reasonable for a four press plant[8]).
- Estimates Made Per Year: 6000 (considering that only 15 to 20 percent of quoted inquiries become firm orders).
- Time and Cost Per Estimate: 1/4 to 1 hour, an average $15 per estimate (considering that 1 man-hour costs about $30).
- Time and Cost for One Die Design: 1 to 8 hours[7,8], about $30 to $240, average $150.
- Manufacturing Cost Per Die: $150 to $1000 or more, average $300.
- Extrusion Tolerances: Average (the dimensions of the extrusion are not close to lower tolerance range, the dimensions of orifices of the same shape in the same die are not exactly identical).
- Average Number and Cost of Trials Per New Die: Two; $10 to $30 per trial, average $20 per trial.

Potential Cost Benefits

For the example plant, described above, the application of CAD/CAM may result in the following cost savings:

(1) Estimating: An average of 50 percent reduction in estimating time is quite realistic. It is reported that for standard structural shapes, this time has been reduced to one-fifth of conventional estimating time[7,9]. This would result in annual savings of $7.5 x 6000 = $45,000 per year.

(2) Die Design: Savings of 20 to 50 percent can be expected[7-9], so that about 33 percent time cost savings, average, is a reasonable assumption. This would result in $50 x 1000 = $50,000 per year.

(3) Die and Template Manufacturing: Considering that most modern die shops use EDM and even wire EDM by optical copying, the advantages of CAD/CAM here would be more in quality, reproducibility, and delivery date than in cost reduction. Nevertheless, average cost reductions may be in the order of 10 percent. This would result in $30 x 1000 = $30,000 per year.

(4) Die Trials: Dies designed by CAD will reduce die trials from two to one trial per die. This would save about $20 x 1000 = $20,000 per year.

(5) Material Yield: The use of CAD/CAM will increase material yield in three ways:

- For a given press, the billet length will be more accurately optimized, so butt length losses will be reduced.
- In multiple-hole dies, the runout lengths will be more even than before, so scrap losses will be reduced.
- The dies will be manufactured to the lower limit of thickness and width tolerances; thus, the extrusions delivered to customers will be lighter in weight, while satisfying tolerance requirements.

As a result, the material yield will increase. It is difficult to estimate how much this increase could be. A probable one percent increase in yield would mean, in our example, 480,000 pounds. With an average cost of $0.75 per pound, this would result in a savings of $360,000. If we assume a 1/2 percent increase in material yield, the savings would be $180,000 per year.

(6) Press Time: The use of optimized billet length and reduction of die trials will also increase press productivity and provide additional press time. Provided this additional press time is used for increased production, additional savings would result. However, these are difficult to estimate and are ignored in the present cost-benefit study.

In summarizing, for the illustrative example plant of 48 million pounds gross (billet weight) capacity, the total potential savings per year would be in the order of:

$ 45,000	Estimating
$ 50,000	Die Design
$ 30,000	Die manufacture
$ 20,000	Die trials
$180,000	Assuming 1/2 percent increase in material utilization
$325,000	TOTAL.

These figures assume that the CAD/CAM system is fully operational and staff has been trained to utilize the system to its full potential. Obviously, for smaller plants, the savings would be correspondingly smaller and the amount of savings for various operational steps would also vary from plant to plant.

The cost of implementing the present CAD/CAM system would depend upon the specific needs of the user. The computer system used by BCL to develop and verify the ALEXTR system represents an investment of approximately $55,000. Since this is a general-purpose computer, it could also be used to handle other computational requirements either of an engineering or business nature. An engineering graphics design computer system, capable of generating fully dimensioned drawings would cost between $100,000 and $150,000. Although this latter system would have more general design capabilities than the BCL computer, ALEXTR and EXTCAM would require considerable modification in order to run on such a computer. Although ALEXTR and EXTCAM are written in FORTRAN, which is available on most computers, software and hardware for handling graphics is usually highly machine dependent. For this reason, programs which are based on using interactive graphics are not as easily transported from one computer configuration to another as a straight batch-run program would be. It can be expected that an amount approximately equal to the cost of the hardware may be necessary to train the staff and to bring the system to a level of full utilization. Thus, for the example plant discussed above, the CAD/CAM systems would be paid off within approximately 18 months. For smaller extrusion plants, the pay-off period may be estimated anywhere from two to four years.

SUMMARY

This chapter describes computer-aided design and manufacturing (CAD/CAM) techniques developed in this program for extrusion of structural shapes of high-strength aluminum alloys. Systems of computer programs called "ALEXTR" and "EXTCAM" were developed for automated design and manufacturing of flat-face dies. The aspects of flat-face die design/manufacture handled by the computer are: (a) selection of optimum number of holes (extrusion orifices) in the die, (b) location of the orifices relative to the billet axis for uniform metal flow through each orifice, (c) modification of the orifice dimensions to correct for thermal shrinkage and die deflection under load, (d) design of bearing lengths to balance metal flow, and (e) machining the dies/template by NC (Numerical Control), EDM (Electro-Discharge Machining) and other methods.

"ALEXTR" and "EXTCAM" were evaluated by conducting extrusion trials described in Chapter III. Volume 2 of this final report is the User's Manual for "ALEXTR" and "EXTCAM".

An economic-technical study is conducted to evaluate the usefulness of CAD/CAM systems in extrusion operations. Results of these evaluations are presented. Reduction in manufacturing costs and delivery schedules, and increase in productivity can be expected from application of CAD/CAM system in a large extrusion operation.

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CHAPTER 3

EXTRUSION OF "TEE" SECTIONS OF ALUMINUM, TITANIUM AND STEEL USING COMPUTER-AIDED TECHNIQUES

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CHAPTER 3

EXTRUSION OF "TEE" SECTIONS OF ALUMINUM, TITANIUM AND STEEL USING COMPUTER-AIDED TECHNIQUES

ABSTRACT

This chapter describes the extrusion trials conducted to evaluate the CAD/CAM techniques developed in this program. A flat-face die for a "Tee" section was designed and manufactured using the computer systems "ALEXTR" and "EXTCAM" described in Chapter II. Billets of high-strength aluminum alloy, Al 7075, were extruded using this flat-face die. Straightness, dimensional accuracy and surface finish of the extrusions were evaluated. In addition, the measured extrusion loads were compared with loads predicted by the computer programs.

The computer system "SHAPE" developed in Phase I and extended in Phase II of this program to complex sections was utilized to design and manufacture a streamlined die for extruding a second "Tee" section. Billets of titanium alloy Ti-6Al-4V, and AISI 4340 steel were extruded through this streamlined die using suitable lubrication systems. Limited trials, with Al 7075 material, were also conducted. The results of these trials were evaluated in regards to product straightness, and surface finish. These results, together with comparison between measured and predicted values of extrusion loads, are presented in this chapter.

INTRODUCTION

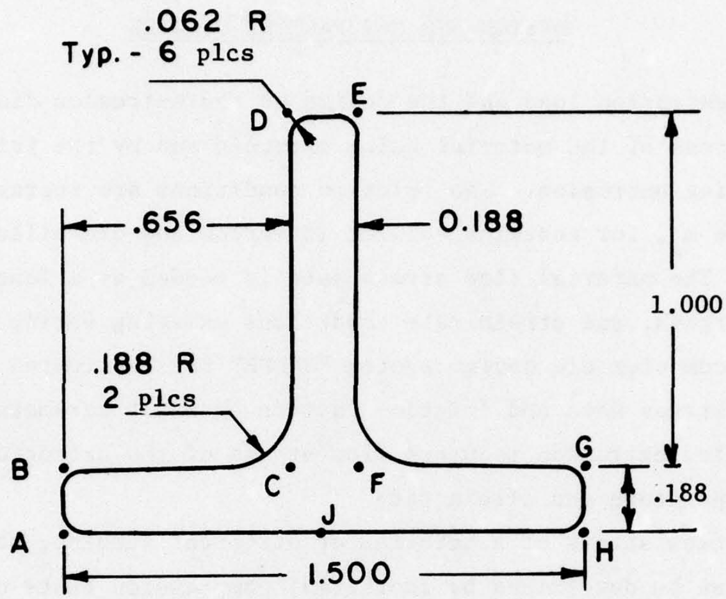
In this project, two interactive computer systems, namely, "SHAPE" and "ALEXTR" are developed for extrusion of aluminum, titanium and steel structural parts used in military hardware. "SHAPE" was developed in Phase I for lubricated extrusion of simple shapes and is extended in Phase II to more complex structural shapes. "SHAPE" can be used to design and manufacture optimum shaped streamlined dies. "ALEXTR" is the system of computer programs for designing the flat-face dies for nonlubricated extrusion of structural shapes from high-strength aluminum alloys. The NC tapes used for manufacturing the computer-designed flat-face die are generated by "EXTCAM" computer system which was also developed in this project. Chapter I and Chapter II of this report describe the capabilities of these interactive computer systems.

Extrusion trials, simulating actual production conditions, were conducted to check the validity and to demonstrate the usefulness of the developed computer systems. "Tee" sections of dimensions typical of extruded structural shapes used in military hardware were produced. Results of the extrusion trials are presented in detail in this chapter.

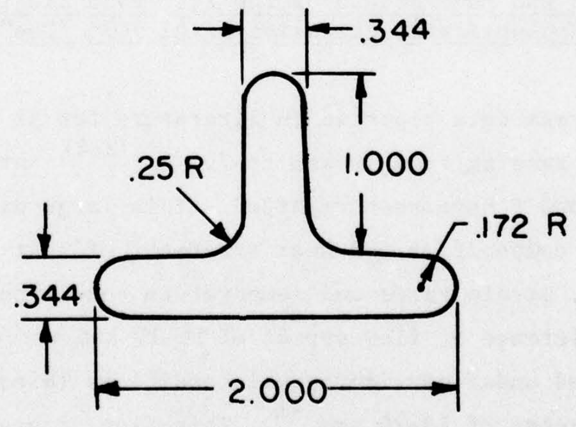
PRODUCT SHAPE AND DIMENSIONS

A structural section commonly used in manufacture of military hardware is the "Tee" section. Therefore, in these trials, the standard "Tee" sections, shown in Figure 1, were chosen as the shapes to be extruded. For evaluating "ALEXTR" and "EXTCAM" interactive die design and die manufacturing systems, a 1-1/2" x 1" x 3/6" Tee section of high-strength aluminum alloy (Figure 1a) was selected, and for evaluating the interactive design system "SHAPE", 2" x 1" x 11/32" Tee sections of Ti-6Al-4V and AISI 4340 steel (Figure 1b) were chosen. These "Tee" sections are typical of structural "Tees" used to manufacture military airplanes and helicopters(1).

The trials were conducted using a 700-ton vertical hydraulic press located in the Metalworking Laboratory of Battelle's Columbus Laboratories. This press has the necessary tooling for conducting hot extrusion of aluminum, steel and titanium. This existing tooling was used. With a container of 3.008 inches inside diameter, the extrusion ratio in extruding Al 7075 "Tee" was 15:1 and in extruding Ti-6Al-4V and 4340 steel "Tees" were approximately 7:1.



(a) Al 7075 "TEE" SECTION



(b) Ti-6Al-4V AND 4340 "TEE" SECTION

FIGURE 1. PRODUCT SHAPES EXTRUDED IN THE TRIALS

DESIGN AND MANUFACTURE OF DIES

The extrusion load and the design of the extrusion die are influenced by the flow stress of the material being extruded and by the friction conditions prevailing during extrusion. The friction conditions are represented by the factors, m_c and m_d, for container-billet interface and die-billet interface, respectively. The material flow stress data is needed as a function of temperature, strain, and strain rate conditions existing during the extrusion process. The computer die design system "SHAPE" for lubricated extrusion requires material flow-stress data and friction factors as input parameters. "ALEXTR" for nonlubricated extrusion requires flow stress of the extrusion material at the applicable temperature and strain rate.

The flow stress of a material at different strains, strain rate and temperatures can be determined by isothermal compression tests or by torsion tests. The extensive experimental effort required to generate this data for the three materials, Al 7075, Ti-6Al-4V, and AISI 4340, was, however, beyond the scope of this project. A simpler approach which utilized (a) existing data in the literature, and (b) rod extrusion trials with these materials was adopted.

Design and Manufacture of the Flat-Face Die for Nonlubricated Extrusion of Al 7075 "Tee"

The flow-stress data reported in literature for Al 7075 differs considerably. Values ranging from 19 ksi to 7.5 ksi[2-4] at extrusion temperatures of 750 - 800 F have been reported. This large difference is due to (1) variations in the composition and heat treatment of test materials, and (2) difference in strains, strain rates and temperature conditions at which tests are conducted. In Reference 9, flow stress of 16-19 ksi was obtained for Al 7075 by ring tests conducted under non-isothermal conditions (dies at 375 F, rings at 800 F) and at strain rates of 13-20 sec^{-1}. This flow stress value cannot be used for conventional hot extrusion of Al 7075 which is done under nearly isothermal conditions and at much lower strain rates. In the present trials, for an extrusion ratio of approximately 15:1 and ram speed of 6 ipm (extrusion speed of 7.5 fpm), the average strain and strain rate, calculated using the equations given in Reference 5 were:

- Average strain = 4.0
- Average strain rate = .37 sec^{-1}.

Akeret and Stratman[3] have reported a value of 13 ksi for flow stress of Al 7075 at the typical extrusion temperatures. The authors, however, do not state how they obtained this value. For a particular Al 7075 section, for which the actual (measured) load was available, extrusion load was predicted taking flow stress equal to 13 ksi. The load predicted from "ALEXTR" was much higher than the actual load. This value therefore, seems to be too high.

Using the data supplied by an extruder for maximum load, container diameter, billet length, and section area, the flow stress was back-calculated using "ALEXTR". Typical values for section perimeter and bearing lengths had to be assumed in the calculations as actual data on these parameters were not available. The calculated values ranged from 5 ksi to 8.5 ksi. For the present trials, the design of the flat-face die for the "Tee" section, shown in Figure 1a, was performed using a flow stress of 7.5 ksi for Al 7075. It may be mentioned here that, in the die design, the die dimensions and layout are not affected by the material flow stress. The flow stress only influences the prediction of extrusion load and die stresses. As shown later, with 7.5 ksi flow stress, the load and the stresses are well below the maximum limits of press capacity and allowable yield stress for the H13 tool steel, respectively.

For the purpose of determining the actual flow stress, a flat-face die with a circular hole equal in area to that of the "Tee" section (Figure 1a) was also fabricated.

Flat-Face Die for the "Tee" Section

The coordinates and the radii used to describe the polygon representing the "Tee" section, shown in Figure 1a, are given in Table 2.

This section was to be extruded using Battelle's 700-ton hydraulic press equipped with a 3-inch container. With an average bearing of 0.187 inch, starting billet dimensions of 2.875-inch diameter x 6.0-inch long, and flow stress of 7500 psi, a breakthrough load of 263 tons was calculated. When the average bearing was specified to be 0.250 inch, the expected load was 273 ton. These extrusion loads are well below the capacity of the press.

TABLE 2. "T" POLYGON COORDINATES

Point	X	Y	R
A	0.000	0.000	0.062
B	0.000	0.188	0.062
C	0.656	0.188	0.187
D	0.656	1.188	0.062
E	0.844	1.188	0.062
F	0.844	0.188	0.187
G	1.500	0.188	0.062
H	1.500	0.000	0.062

The opening was positioned in the die using the program-generated layout. That is, the center of gravity of the section was located at the center of the container. This is shown in Figure 2. The next step in the design was to provide the cave or dish compensation. This was applied to the long side of the base of the "T". Points H and A (Figure 1a) were indicated as the cave axis end points and then a new point, J, was added. The cave compensation was 0.004 in/in.

The stress on the tongue was then determined. The tongues were defined by points BCD and EFG (Figure 1a). The tool dimensions were as follows:

- Die thickness: 1.0 inch
- Backer thickness: 1.75 inch
- Bolster thickness: 0.0 inch
- Die to backer clearance: 0.125 inch.

Although the average pressure on the die was 74,300 psi, the combined bending and shear stress was only 1573 psi on the die and 11,100 psi on the backer. If no backer was used, the tongue stress on the die would have been 40,600 psi. These stresses are well below the yield strength of H13 die material. The calculations also show that there is no need for a conforming bolster for this particular section.

The final step in the die design process was to indicate the section thicknesses and bearing transition points. Two thicknesses were identified. These thicknesses and the bearing transition points are shown in Figure 3. The die design data was then stored on a disk file for subsequent access by program "EXTCAM". The results of the "ALEXTR" analysis which were sent to the print file on the disk are given in Figure 4.

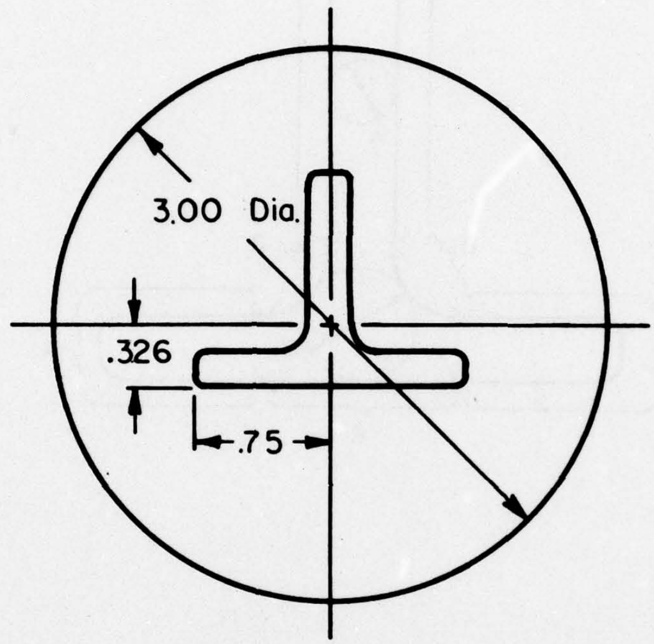


FIGURE 2. POSITION OF "T" SHAPE IN THE FLAT-FACE DIE

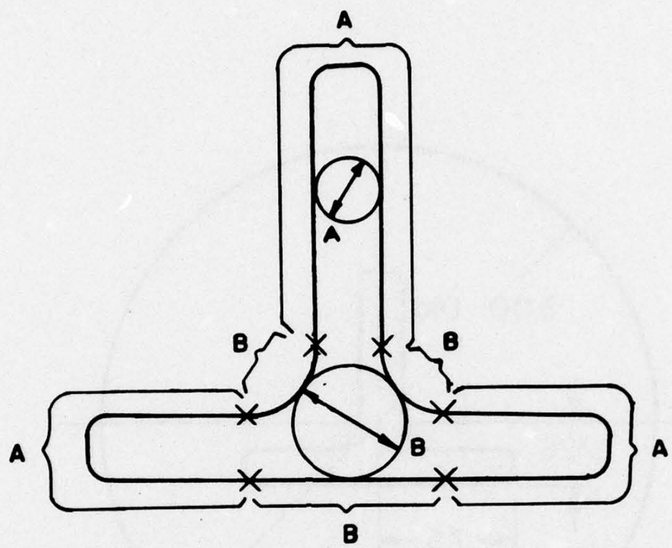


FIGURE 3. SECTION THICKNESSES AND TRANSITION POINTS USED IN THE DESIGN OF THE BEARINGS FOR FLAT-FACE "T" DIE

```
THIS IS DATA FOR BATTELLE LABS EXTRUSION TESTS

   1.5 X 1.2 X 3/16 TEE SECTION

 SECTION NO.      2
 CROSS-SECTION AREA =      0.480  PERIMETER =      5.06  SHAPE FACTOR    8.78
 COORDINATES OF CENTROID ARE X =    0.750       Y =    0.327
 CIRCUMSCRIBING CIRCLE DIAMETER    1.63  CENTER AT X =   0.749, Y =   0.373

 PRESS SYSTEM NO. 4, CAPACITY (TONS):  700., CONTAINER DIAMETER:  3.000
 BILLET -- DIAM:   2.875,  MAX LENGTH:  6.0, AREA:   6.5,  WEIGHT:    3.9
 BUTT LENGTH:  1.0,  RUN-OUT LENGTH (FT):  20,  MAX. NO. OF OPENINGS:  1
 SPEED(FPM):    5., CYCLE TIME (SECS): 60.,  EXTRUSION RATIO:  14.7

 WITH STANDARD BILLET, 1 HOLES, AND    5 FOOT EXTRUDED LENGTH,
 RECOVERY RATIO IS 73.9%, EXTRUSION RATIO:  14.7
 THIS GIVES  5 -  1 FOOT MULTIPLES, AND  0 FOOT LOSS PER HOLE.

 WITH    5. FPM EXTRUSION SPEED, AND  60. SEC. CYCLE TIME,
  30.0 PRESS CYCLES PER HOUR CAN BE RUN
 THIS GIVES   117. BILLET POUNDS AND    86. EXTRUDED POUNDS PER HOUR

 BEST YIELD WITH SPECIFIED OPENINGS
 NUMBER OF HOLES:  1, EXTRUDED LENGTH:   5
 BILLET LENGTH:  5.5, RECOVERY RATIO: 80.3%, EXTRUSION RATIO:  14.7
  5 -  1 FOOT PIECES PER HOLE

 WITH  1 OPENINGS, THE BREAKTHROUGH LOAD IS   253. TONS.

 TONGUE PRESSURES:    2770. 68818.      0.
 TONGUE STRESSES:     1457. 10276.      0.

 TONGUE PRESSURES:  71587.     0.       0.
 TONGUE STRESSES:   37647.     0.       0.
```

FIGURE 4. RESULTS OF ALEXTR ANALYSIS FOR "T" SECTION (Note: The information related to the production rate is not used in the present trials)

EXTCAM was used to make the tapes to NC machine the EDM electrodes and the die bearings. To machine the graphite electrodes, two tapes were made. The first, used for roughing, had an 0.375-inch diameter cutter specified; for the finish pass, an 0.250 cutter was specified. For both passes, an EDM burn and polish allowance of 0.002 inch was used. Also, before the electrode or bearing tapes were generated, the section dimensions were increased by 1.6 percent to compensate for thermal shrinkage and thinning during stretching.

The electrode and the die were machined on the CNC milling machine at Battelle. On the first machining pass on the electrode, an 0.250-inch diameter cutter was used, although an 0.375-inch diameter cutter had been specified when generating the tape. This resulted in the electrode being left 0.062 inches oversize all the way around. After the roughing pass was completed, the excess stock beyond the projection was removed. This was done by manual operation of the joystick position controller which is a feature of the BCL/CNC machine control. The finish cut on the electrode projection was then made using an 0.250-inch diameter cutter and the finish pass tape.

When generating the tape to machine the bearings, the following specifications were used:

- Diameter cutter: 0.250 inch
- Cutter offset from die opening: 0.062 inch
- Minimum bearing length: 0.187 inch.

The die was machined to overall size in a lathe. The bearings were then NC machined into the back of the die. In machining the bearings, a cutter with 5-degree taper per side and an 0.250-inch diameter tip was used. The tapered cutter provided both a more rigid cutting tool than a standard ball mill of the same size, and also provided additional clearance from the opening at the back of the die. After heat treating the H13 die steel to R_c 42-46, the actual section opening was EDM'ed through the die from the front. A 1.75-inch thick die backer was made with a straight through opening by conventional milling rather than NC machining. The backer was also made from H13 tool steel and hardened to R_c 42-46.

Figure 5 shows the finished die and backer. Figure 6 and 7 show a model of the die. This was made from aluminum and machined in the same way as the steel die. It was sectioned as shown to permit close examination of the bearing contours. Figure 8 is a plot of the cutter path which generated the bearings. Figure 9 is a plot of the cutter path used to cut the electrode.

Flat-Face Die for the Round Section (Rod)

As mentioned earlier, to back calculate the flow stress of the Al 7075 material, circular sections (rods) of the same material were also extruded using a flat-face die. These rod extrusion trials also provided valuable information about the effect of section shape on the extrusion load. The process conditions, including the reduction ratio, were kept the same as for "Tee" section extrusions. The area of the circular cavity was equal to the area of the "Tee" section shown in Figure 1a.

Figure 10a shows the die drawing with the overall die dimensions. These overall dimensions were used for all dies made as part of this program. Figure 10b shows the fabricated die along with the flat-face "T" die. The die was machined from annealed H13 bar stock to overall size on a lathe. It was then heat treated to R_c 42-46. The inside diameter and the two faces were ground as shown in Figure 10a.

Design and Manufacture of Streamlined Dies for Extrusion of Steel and Titanium "Tees"

The dependence of flow stress ($\bar{\sigma}$) on temperature, strain, and strain rate is different for 4340 steel and Ti-6Al-4V materials. Also, the friction conditions at the die material and container material interfaces during extrusion are different for these materials as different lubrication systems are used. The 4340 steel was precoated with Polygraph, whereas Ti-6Al-4V was coated with 0010 glass. The die design system "SHAPE" would calculate different optimal die lengths for extruding steel and titanium materials since input parameters $\bar{\sigma}$, m_c, m_d are different for these materials. However, in the trials, the same streamlined die

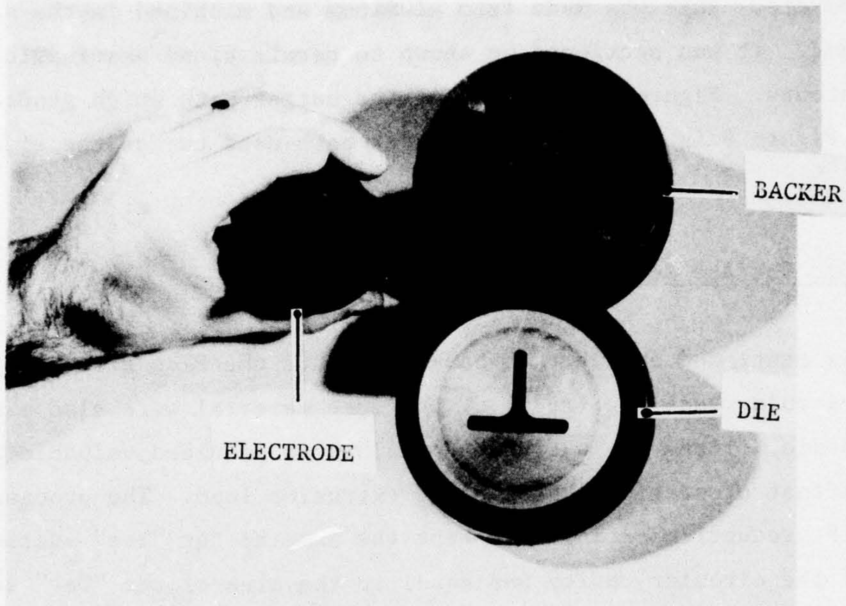


FIGURE 5. DIE AND BACKER FOR "T" SHAPE MADE DURING ALEXTR and EXTCAM

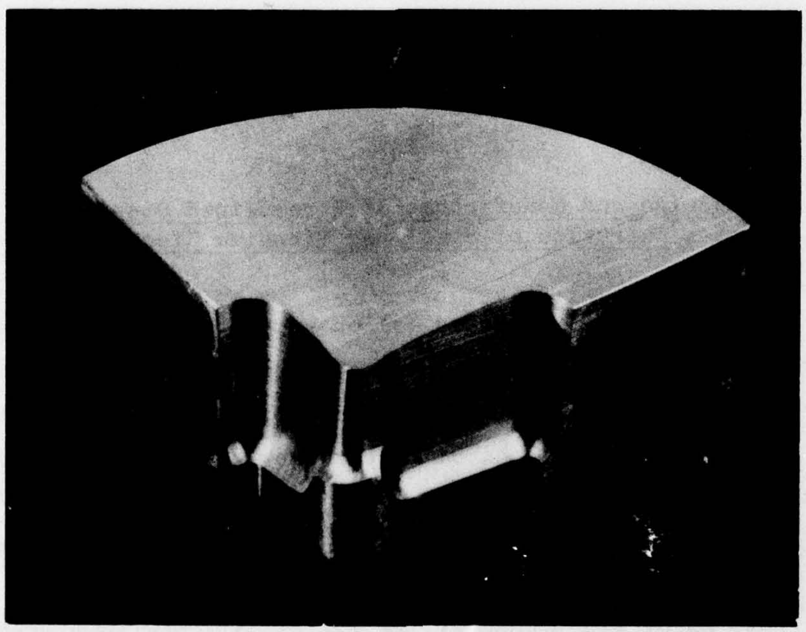


FIGURE 6. SECTIONED MODEL OF FLAT-FACE "T" DIE SHOWING VARIATION OF BEARINGS

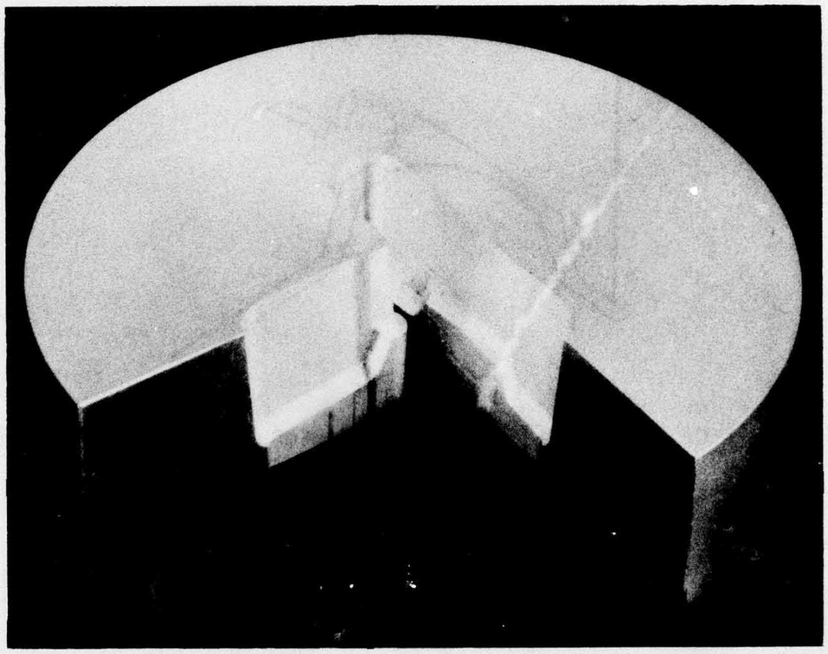


FIGURE 7. SECTIONED MODEL OF DIE SHOWING VARIATION OF BEARINGS

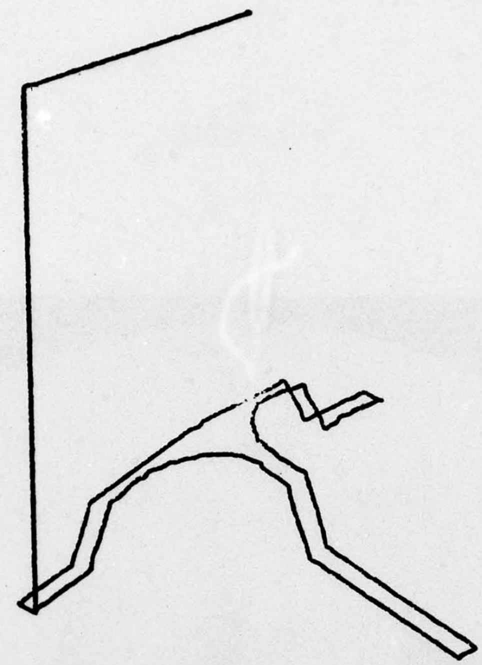


FIGURE 8. PLOT OF CUTTER PATH TO CUT BEARINGS INTO THE FLAT-FACE "T" DIE

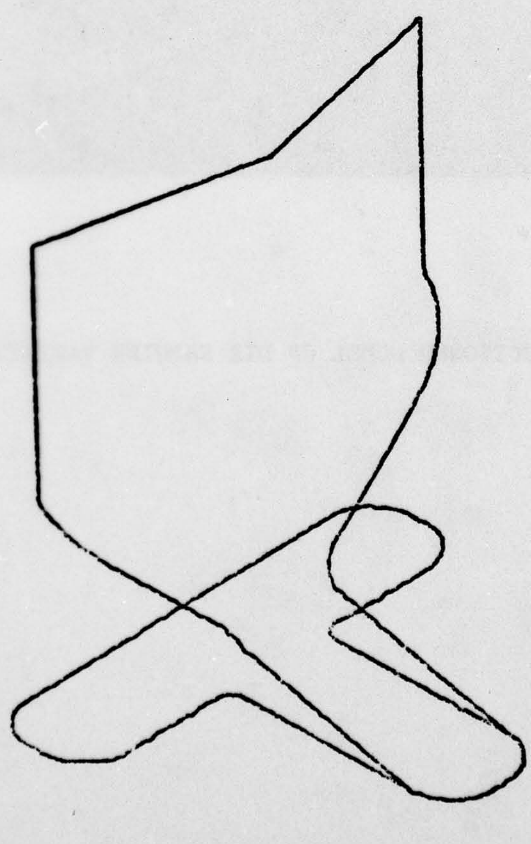


FIGURE 9. PLOT OF CUTTER PATH TO CUT EDM ELECTRODE FOR FRONT OPENING OF THE FLAT-FACE "T" DIE

was to be used for both steel and titanium extrusions. The design of this streamlined die for the "Tee" section (Figure 1b) was, therefore, performed assuming constant flow stress for the material and average values of m_c and m_d taken from published literature.

As mentioned earlier, extrusion trials were conducted using a 700-ton hydraulic press with a container diameter of 3.00 inches and rated maximum speed of 80 ipm under load. At this speed, the average strain and strain rate during extrusion are approximately equal to:

- Strain = 2.6
- Strain rate = 3.31 sec^{-1}.

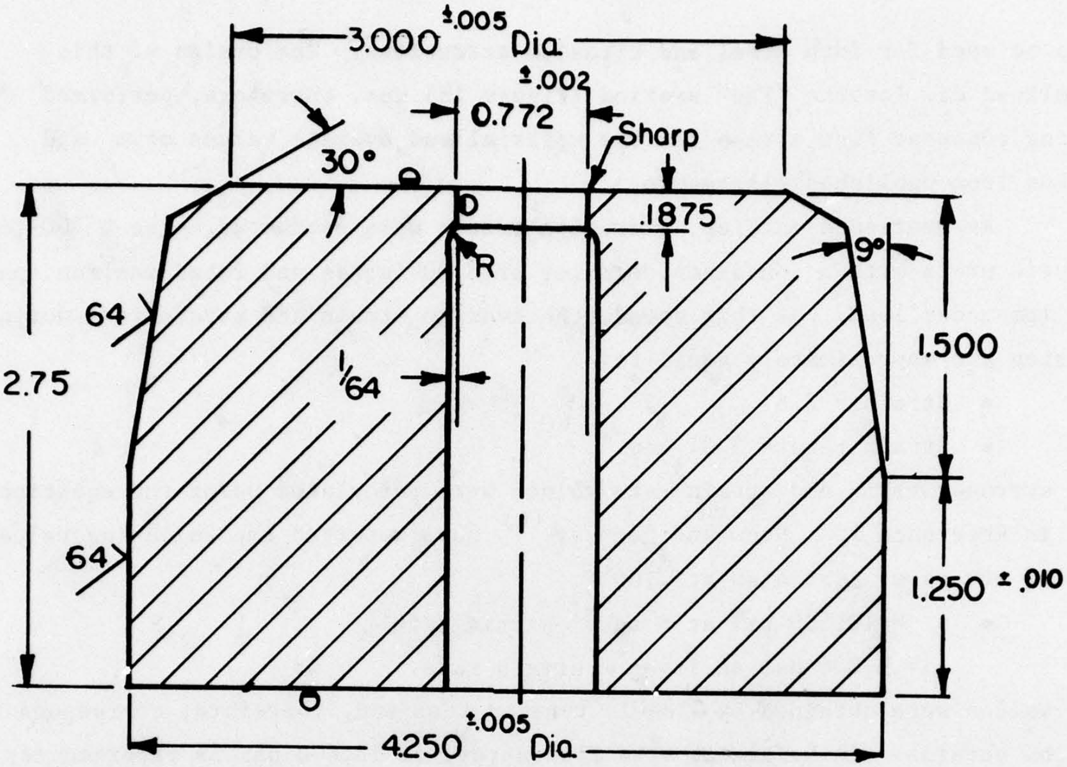
These average strain and strain-rate values were calculated using the equations given in Reference 5. Scow and Dempsey [6] have reported the following values for flow stress of AISI 4340 at 2100 F:

- $\bar{\sigma}$ = 10,500 psi at 6 sec^{-1} strain rate
  = 9,000 psi at 1 sec^{-1} strain rate.

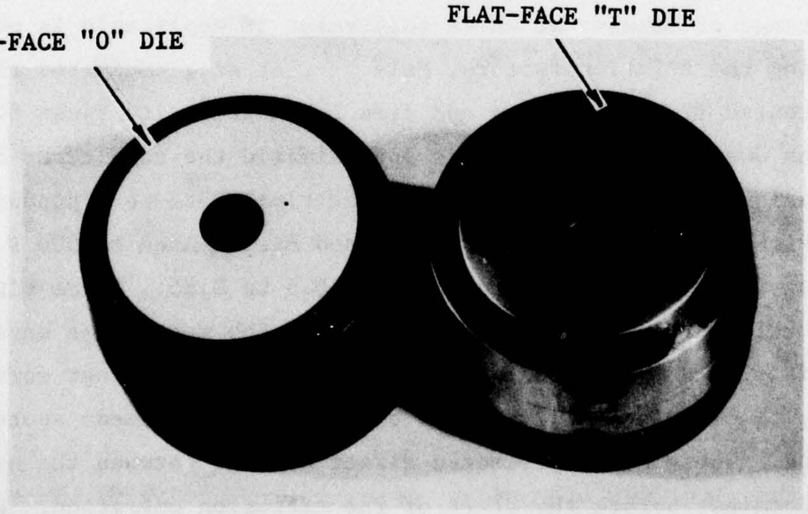
These values were obtained by Gleeble tension test and, therefore, correspond to very low strains. In Reference 4, a flow stress of 15,600 psi is reported for AISI 4337 corresponding to 2100 F temperature, 3.31 sec^{-1} strain rate and 0.70 strain. For Ti-6Al-4V, $\bar{\sigma}$ = 16,400 psi is given by DePierre [7] at a temperature of 1750 F. The range of strains at which this value is applicable is not known.

Regarding the friction factors, Male [8], et al., conducted ring tests with 0010 glass coated Ti-6Al-4V rings and dies lubricated with Fiske 604D. The process conditions during these ring tests approximated the conditions during the present extrusion trials with Ti-6Al-4V. The ring tests were conducted in a hydraulic press with a ram speed of 1.5 in/sec and dies heated to 500 F. The measured values of friction factor m ranged from 0.5 to 0.85. These high m values can be partially attributed to die chilling effect which was not as severe in the extrusion trials. In the present trials, the die and container were heated to 750-800 F. Also, to minimize chilling, the billets had weld beads spotted at three places at each end. These beads prevented direct contact between the hot billet and the colder container before the start of the extrusion operation. Less chilling would give a lower effective friction factor.

Based on these reported values of $\bar{\sigma}$ and m, the following input values were used in designing the streamlined die.



(a)



(b)

FIGURE 10. FLAT-FACE "O" DIE USED IN NONLUBRICATED EXTRUSION OF Al 7075

- $\bar{\sigma}$ = 15,000 psi
- $m_c = m_d = 0.4$.

As done in the case of the nonlubricated extrusion trials, circular sections (rods) of 4340 steel and Ti-6Al-4V were extruded using a conical die to back calculate average flow stress values. These rod extrusion trials also provided information on the effect of section shape on the extrusion load.

Streamlined "T" Die for Ti-6Al-4V and 4340 Steel

Figures 11-14 show some of the information printed on the CRT during the interactive design process. The input parameters which include the coordinates and radii describing the "Tee" section, billet length, container diameter, extrusion temperature, etc., are shown in Figure 11. The output of the analysis performed by "SHAPE" are shown in Figure 12. The output includes extrusion ratio, die length, various components of pressure, total mean extrusion pressure and total extrusion load. The extrusion load of 274 tons is well within the capacity of the press which is 700 tons. The mean extrusion pressure of 76912 psi is also within the maximum pressure for which the container and tooling are designed.

The pressure distribution along the die length is shown in Figure 13. An approximate calculation using overall die dimensions, ID profile and die pressure distribution indicated that the circumferential tensile stresses are less than the allowable yield strength of hardened H13 steel at 750 F. A one piece die, therefore, had sufficient strength to withstand the extrusion pressure. The existing backup tooling could, therefore, be used in the trials.

Figure 14 shows the cutter path for NC machining the EDM electrode. "SHAPE" indicated that undercutting (gouging) would occur with a 1/2-inch diameter ball end mill. When the cutter diameter was reduced to 3/8 inch, no gouging was predicted. Thus, a 3/8-inch cutter diameter was specified when the cutter path plotted in Figure 14 was generated. The NC tape generated from "SHAPE" was used to machine the EDM electrode. The machined electrode surfaces were polished by hand. The die blank was turned from H13 annealed bar on a lathe and the back relief was milled using conventional milling. 1/4-inch holes were drilled through

INPUT

RADIUS OF THE BILLET (IN)	,RAD =	1.505
INTIAL TEMPERATURE OF THE BILLET (F)	=	1725.000
SPEED OF THE RAM (IN/SEC)	,VO =	1.333
LENGTH OF THE BILLET (IN)	,LO =	6.000
LENGTH OF THE DIE LAND (IN)	,LD =	.313
FRICTION SHEAR FACTOR AT CONTAINER	,MC=	.400
FRICTION SHEAR FACTOR AT DIE	,MD=	.400
MATERIAL CODE,	IMATER =	8
DIE CURVE CODE,	NCURVE =	1

POINTS DEFINING EXTRUSION SHAPE

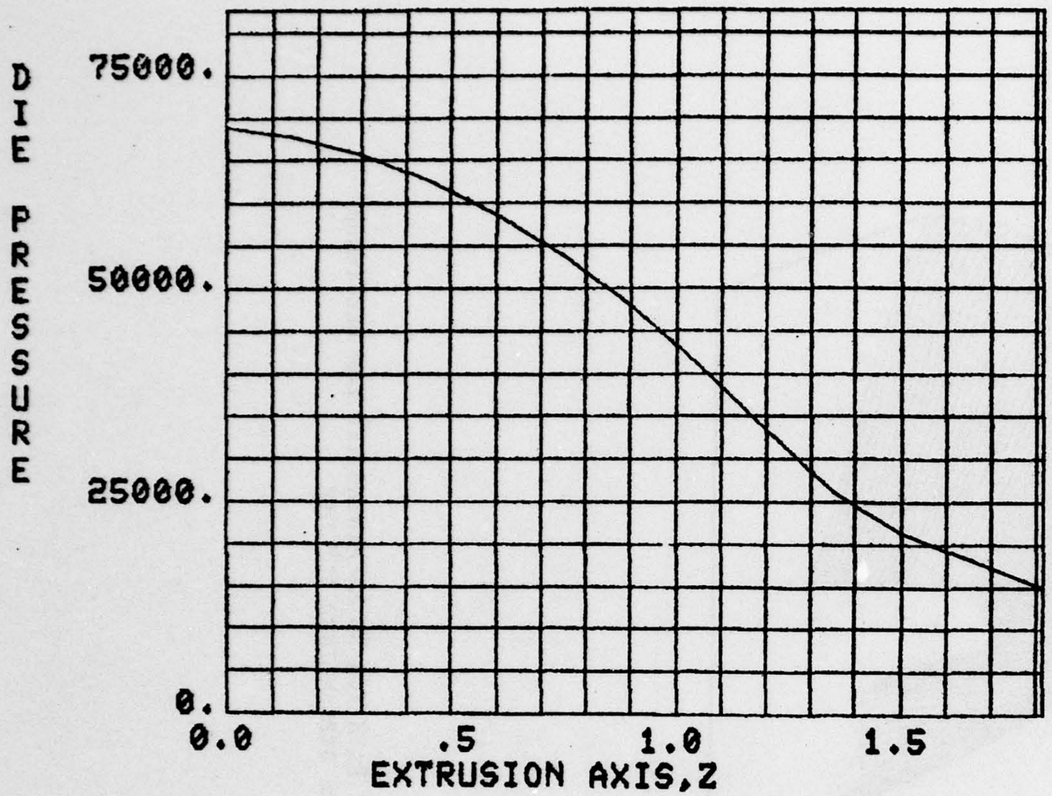
X	Y	R
.3310	0.0000	0.0000
.3310	1.0000	.1700
-.0130	1.0000	.1700
-.0130	.1720	.2500
-1.0130	.1720	.1700
-1.0130	0.0000	0.0000
.3310	0.0000	0.0000

FIGURE 11. INPUT PARAMETERS USED IN CAD/CAM OF STREAMLINED "T" DIE

OUTPUT

CROSS-SECTIONAL AREA OF THE BILLET	,AO=	7.116
CROSS-SECTIONAL AREA OF EXTRUSION	,AF=	1.021
AREA RATIO	(AO/AF)=	6.967
POSITION OF THE NEUTRAL AXIS	,XC=	.087
	YC=	0.000
POSITION OF THE EXTRUDED SHAPE WITH RESPECT TO THE BILLET AXIS	XMOV=	0.000
	YMOV=	0.000
PERIMETER OF THE EXTRUSION SHAPE	=	6.027
DIE LENGTH...OPTIMAL OR SELECTED	=	1.500
VOLUME OF MATL IN THE DIE	=	5.872
SURFACE AREA OF THE DIE	=	13.239
COMPONENT OF EXTRUSION PRESSURE		
DUE TO PLASTIC DEFORMATION	=	29139.980
DUE TO SHEAR AT DIE ENTRANCE AND EXIT	=	.000
DUE TO FRICTION AT CONTAINER	=	23017.286
DUE TO FRICTION AT DIE SURFACE	=	18366.943
DUE TO FRICTION AT DIE LAND	=	6387.792
TOTAL MEAN EXTRUSION PRESSURE	=	76912.002
TOTAL EXTRUSION LOAD	=	547289.3

FIGURE 12. OUTPUT OF DEFORMATION ANALYSIS PERFORMED BY "SHAPE"



Z	DIE PRES.
0.00	68894.7
.15	67748.3
.30	65680.0
.45	62678.1
.60	58720.2
.75	53778.8
.90	47840.8
1.05	40965.8
1.20	33458.4
1.35	26271.8
1.50	21387.8
1.81	15000.0

FIGURE 13. DIE PRESSURE DISTRIBUTION PREDICTED BY "SHAPE"

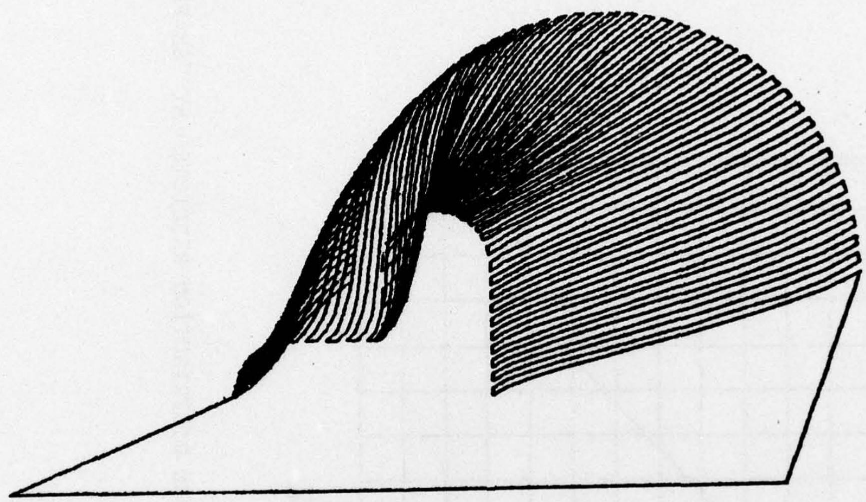


FIGURE 14. CUTTER PATH FOR NC MACHINING THE EDM ELECTRODE FOR THE STREAMLINED "T" DIE

the die from the front to allow passage of the coolant during EDM. The die was then heat treated to R_c 42-46. The hardened die was sunk from the front with the electrode on an EDM machine at Battelle. The die land was hand polished but the rest of the EDM'ed die surface was left rough to retain lubricant. Figure 15 shows the overall die dimensions, the EDM electrode, and the manufactured die.

Conical "O" Die for Ti-6Al-4V and 4340 Steel

Figure 16 shows the conical die manufactured for ext ding bars of Ti-6Al-4V and 4340 steel. As mentioned earlier, these rod extrusion trials were conducted (a) to back calculate the average flow stress of Ti-6Al-4V and 4340 steel under conditions at which the "Tee" extrusions were performed, (b) to determine the effect of product shape on extrusion load, and (c) to "prove out" the lubrication systems selected for the "Tee" extrusions.

The "SHAPE" design programs were used to select the optimal die length. The die was machined on a lathe from annealed H13 bar stock. It was then heat treated to R_c 42-46 and ground on surfaces shown in Figure 16a. Figure 16b shows the manufactured die.

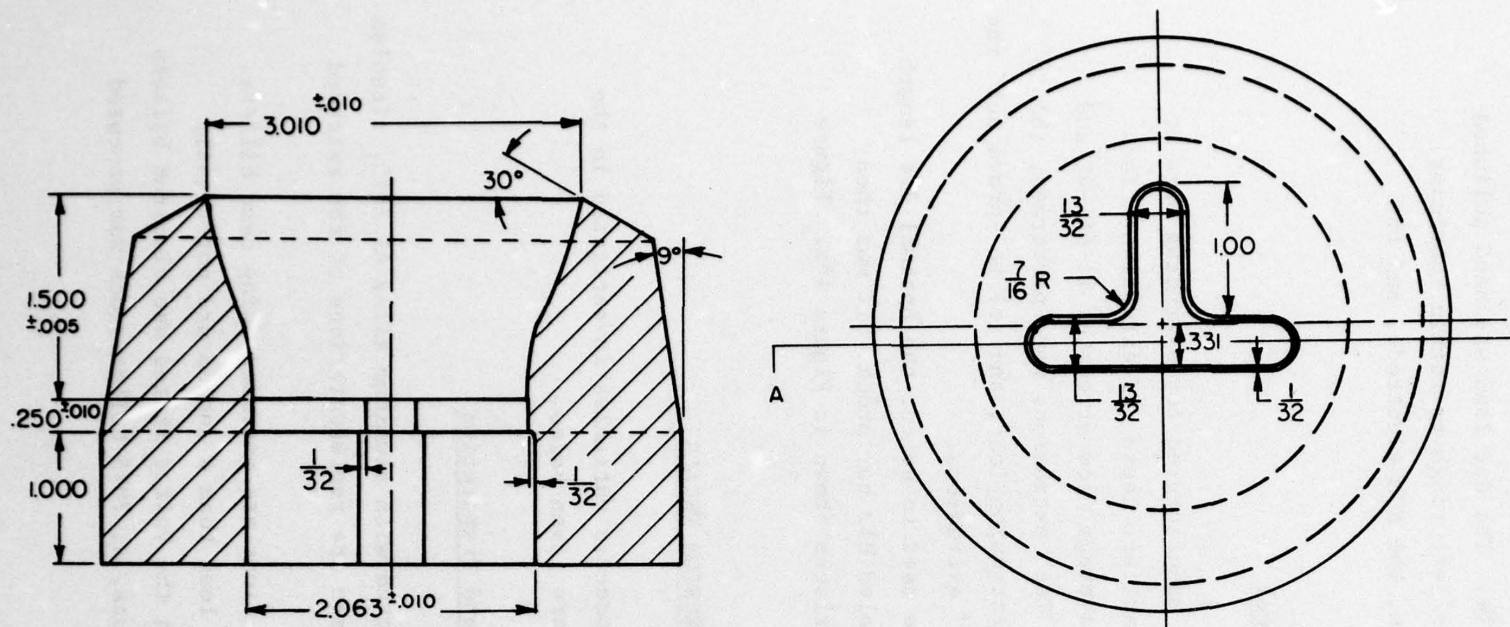
DETAILS OF EXTRUSION TRIALS

Table 1 gives a summary of the process variables investigated in the extrusion trials. Details of the trials are given below.

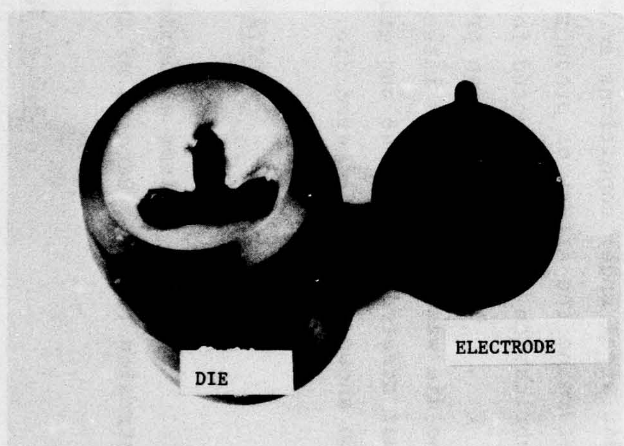
Billet Materials and Preparation

The extrusion trials were conducted with aluminum alloy Al 7075, titanium alloy Ti-6Al-4V, and AISI 4340 steel. These are representatives of the extruded materials used in military hardware.

In normal practice, aluminum sections are extruded using cast billets. However, Al 7075 cast billets of diameter less than 4 inches are not readily available as most all extrusion presses in the United States use aluminum billets of diameter larger than 4 inches. Therefore, Al 7075 billet stock was procured

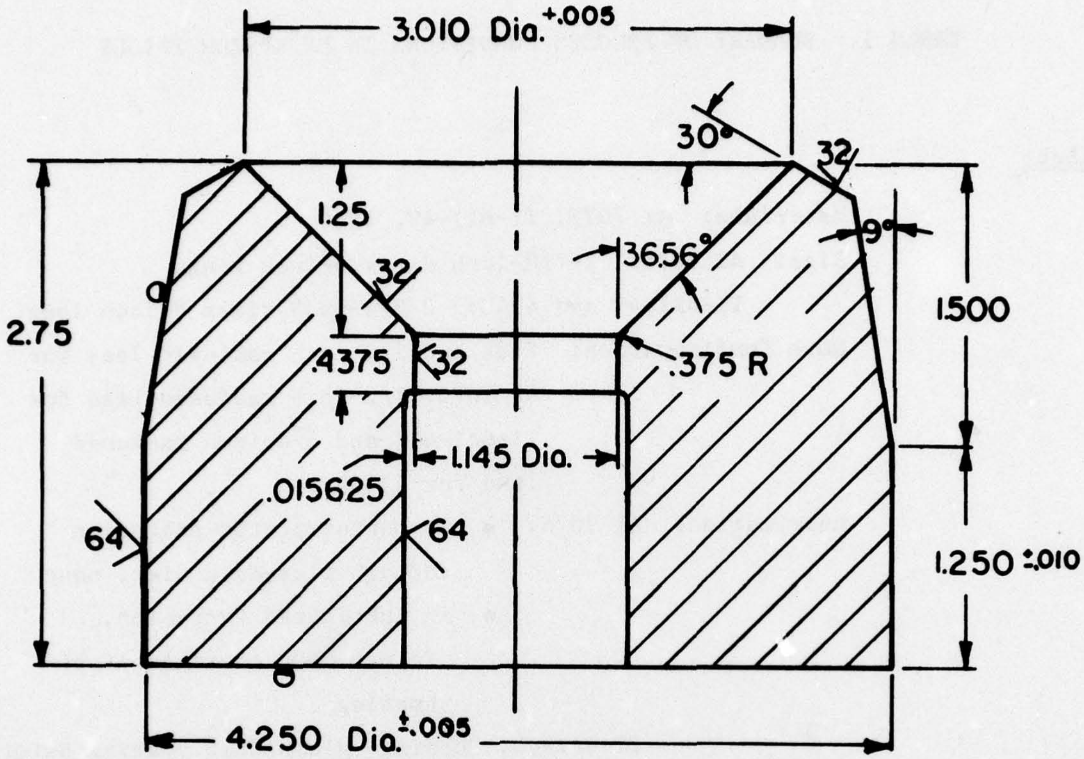


(a) Overall Dimensions of the Streamlined "T" Die

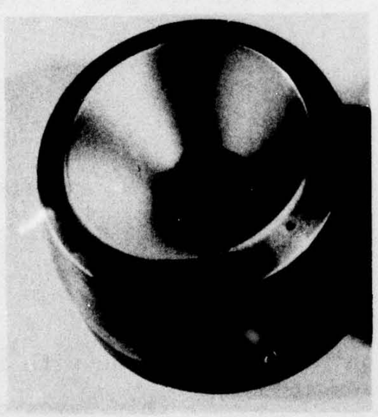


(b) EDM Electrode and Streamlined "T" Die

FIGURE 15. STREAMLINED "T" DIE USED FOR EXTRUDING 4340 STEEL AND Ti-6Al-4V TEES



(a)



(b)

FIGURE 16. CONICAL "O" DIE FOR EXTRUDING RODS OF Ti-6Al-4V AND 4340 STEEL

TABLE 1. SUMMARY OF PROCESS CONDITIONS IN EXTRUSION TRIALS

Billet:

Materials: Al 7075, Ti-6Al-4V, 4340

Size: Al 7075: 2-7/8-inch dia x 6-inch long
Ti-6Al-4V and 4340: 2-3/4-inch dia x 6-inch long

Nose Configuration: Flat and 1/2 inch radiused lead for Al 7075, 1/2-inch radiused lead for Ti-6Al-4V, and 3/4-inch radiused lead for 4340

Lubrication: Al 7075:
- In nonlubricated extrusion through flat-face dies, none
- In lubricated extrusion, Felpro C300 coating before heating

Ti-6Al-4V: Corning glass 0010 coating before heating
4340: Polygraph coating before heating

Temperature: Al 7075: 600 F - 790 F
Ti-6Al-4V: 1690 - 1725 F
4340: 2150 F

Die:

Design: Flat-face, conical and streamline as shown in Figures 5, 10, 15 and 16

Material: H13

Hardness: R_c 42-46

Lubrication: Al 7075: none with flat-face dies, except thin layer of Fiske 604 on flat face of the die to allow butt removal
(also for container)
: Fiske 604 for conical and streamlined dies
Ti-6Al-4V: Fiske 604
4340: Fiske 604

Temperature: 550 - 800 F
(also for container)

Product:

Al 7075: 0.772-inch diameter rod and "T" section (Figure 1a)

Ti-6Al-4V, 4340 and Al 7075: 1.146-inch diameter rod and "T" section (Figure 1b)

Extrusion Ratio: Nonlubricated extrusion: 15:1

Lubricated extrusion: 7:1

Press:

Capacity: 700 tons

Type: vertical-hydraulic press

Container: 3.008-inch diameter

Ram Speed: 80 ipm maximum at full load

Ram Speed:

Lubricated extrusion: 80 ipm

Nonlubricated extrusion: 6 ipm

in "As Fabricated" (F) condition and was annealed before use. The annealing treatment was as follows. Pieces sawed from bar stock were heated to 775 F and held at this temperature for three hours. They were then cooled slowly in still air. The material was heated again to 450 F, held for three hours and cooled to room temperature in still air. The extrusion billets were machined from these annealed pieces. The overall dimensions of the aluminum billets were 2-7/8 inches diameter x 6 inches long. In nonlubricated extrusion through flat-face dies, billets with flat ends were used, whereas billets with 1/2 inch lead-in radius on the nose were used in lubricated extrusion trials.

Ti-6Al-4V material was procured as centerless-ground annealed bar certified to AMS Spec 4928H. 4340 steel was bought in as-fabricated condition. Billets were machined from the Ti-6Al-4V and 4340 bars to overall dimensions of 2-3/4 inch ($\pm$ .005) diameter by 6 inches long. All the billets were given radiused lead-in at the nose (1/2 inch radius for Ti-6Al-4V and 3/4 inch radius for steel).

Billet, Die and Container Lubrication

Nonlubricated Extrusion

In conventional hot extrusion of aluminum alloys through flat-face dies, extrusion is conducted without any lubrication[9]. The die face is sometimes given a light coat of graphite lubricant for easy removal of the butt. In the present trials through flat-face dies, the conventional practice of no lubrication was followed in that a thin coating of Fiske 604 was used on the die face only. This lubricant contains graphite in mineral oil and is manufactured by Fiske Brothers Refining Company, Toledo, Ohio. The container and the billet were not lubricated.

Lubricated Extrusion

Steel and titanium are extruded using a variety of graphite and glass lubricants. To date, however, only glass lubricant has worked successfully on a production basis in extruding long lengths. In the Sejournet process, the heated billet is commonly rolled over a bed of ground glass, or it is sprinkled with glass powder which supplies a layer of low-melting glass to the billet

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COMPUTER-AIDED DESIGN AND MANUFACTURING FOR EXTRUSION OF ALUMIN--ETC(U)
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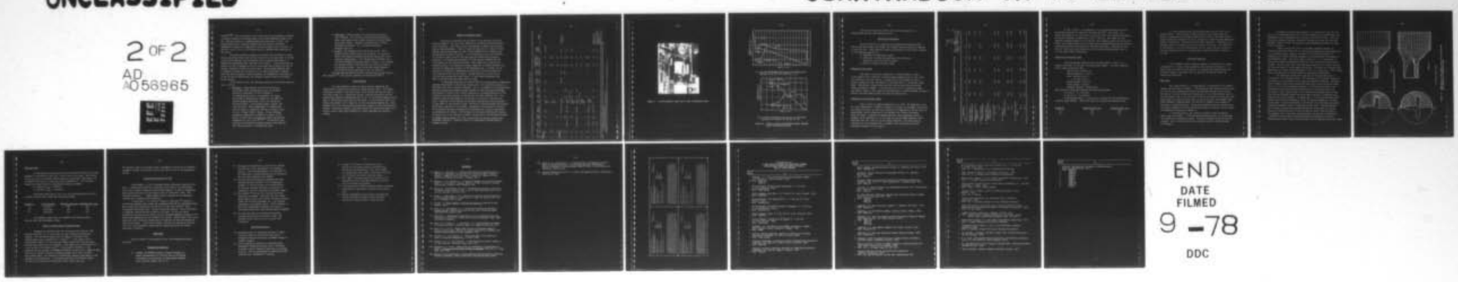

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surface[10,11]. Prior to insertion of the billet into the hot-extrusion container, a suitable die glass lubricating system is positioned immediately ahead of the die. This may consist of a compacted glass pad, glass wool, or both. The prelubricated billet is quickly inserted into the container followed by appropriate followers or a dummy block, and the extrusion cycle is started. At the end, a butt is left in the container which is removed before starting the next cycle.

The unique features of glass as a lubricant are its ability to soften selectively during contact with the hot billet and, at the same time, to insulate the hot-billet material from the tooling, which is usually maintained at a temperature considerably lower than that of the billet. In the glass-extrusion process, the die is designed not only to avoid shear flow of metal, but also to provide a reservoir of glass on the die face. The die design generally used by companies licensed for the process is a flat-face design with a radiused entry into the die opening. During extrusion, the combination of the glass pad on the die and the uniform metal flow produces a nearly conical flow towards the die opening.

In the present trials, The lubricants employed with different materials were as follows:

- Ti-6Al-4V. Before heating, the billets were given a precoating of 0010 Corning glass as per the procedure specified in Reference 12. This consisted of (a) degreasing the billet, (b) dipping it in a glass slurry made by mixing water, Carbopol No. 934, NaOH and 100 mesh powdered 0010 glass, and (c) air drying the dip-coated billet. This procedure gives a precoat .015 - .025-inch thick. 0010 corning glass is a potash-soda-lead type glass of composition (63 SiO_2, 7.6 Na_2O, 6 K_2O, 0.3 CaO, 3.6 MgO, 21 PbO, 1 Al_2O_3). It has a working temperature (temperature at which the viscosity is 10^4 poises) of 1801 F and is suitable as precoat for extrusion temperatures as low as 1750 F[12-13]. The heated die and container were brushed and swabbed liberally with Fiske 604 just before the start of the extrusion cycle.

- 4340 Steel. Before heating, the billets were dip coated with Polygraph. This lubricant contains micronized graphite powder and powdered boron nitride suspended in a water-soluble amine-amide complex. Polygraph is manufactured by United International Research, Inc., 230 Marcus Boulevard, Hauppauge, New York.
- Al 7075. The aluminum billets were heated to 250 - 300 F, dipped in Felpro C300 solution and air dried. The lubricant Felpro C300 contains molybdenum disulphide (MoS_2) with a semi-inorganic bonding agent. It is manufactured by FEL-PRO, Inc., 7450 North McCormick Boulevard, Skokie, Illinois. The container was swabbed liberally with Fiske 604 just before the start of the extrusion process. Also, the die was brushed liberally with Fiske 604 before inserting it into the container.

The lubricants mentioned above were selected based on the results of past studies[1,14], and previous experience at Battelle and AFML[9].

Billet Heating

The time required to attain the desired billet temperature was established for various billet materials through heating trials. Two thermocouples were attached to the test billet; one at the end face and the other in the billet center at 1.5 inches from the end. The time after which both the thermocouples indicated temperatures within $\pm$ 25 F of the desired temperature was taken as the minimum heating time for the billet. In the extrusion trials, the billets were heated in the furnace for at least the minimum heating time. Bare aluminum billets for nonlubricated extrusion were heated in a hot circulating air furnace. Lubricated Ti-6Al-4V, 4340 steel and Al 7075 billets were heated in an electric furnace under argon atmosphere to prevent degrading the lubricant coating.

RESULTS OF EXTRUSION TRIALS

The process conditions and the results of the extrusion trials are listed in Table 2. The trials were conducted in the 700-ton vertical hydraulic press at Battelle. This press is fully instrumented to measure the extrusion load and ram displacement. Figure 17 shows the press set up. Figure 18 shows typical load and displacement vs time records obtained for the nonlubricated and lubricated extrusion processes. It is interesting to note the difference in the load vs time curves for the lubricated and nonlubricated extrusion processes. In nonlubricated extrusion, the load reaches a maximum and then drops steadily as the extrusion proceeds. This steady drop in load during extrusion is due to (a) reduction in billet length and in billet-container friction and (b) temperature increase in the deformation zone. In Figure 18, the extrusion is considered to begin when the load starts to build up while the billet material fills the die orifice. Because the load is plotted versus time the load increase has a small slope. If load versus displacement was shown, then this slope would have been very steep.

In lubricated extrusion of Ti-6Al-4V "Tees", the load peaks at breakthrough and then drops rapidly to the initial running load. The load then increases at a steady but slow rate as extrusion proceeds. This is in contrast to the nonlubricated extrusion process which showed a steady decrease in load following breakthrough. This increase in load for the Ti-6Al-4V extrusion is attributed mainly due to the chilling of the billet surface in contact with the colder container wall. The lubricant Fiske 604 was brushed on the die face at the start of the extrusion trial. Depletion of this lubricant as extrusion continues also would contribute to some extent to the increase in load. The billet chilling increases the material flow stress, especially at the surface. Components of the load due to friction at the material-container and material-die interfaces are directly proportional to the material flow stress. This increase in flow stress overrides the decrease in friction due to the reduction in surface contact area as the extrusion proceeds. In nonlubricated extrusion of Al 7075, the extrusion is conducted under nearly isothermal conditions. Therefore, there is no significant chilling effect to increase the load.

TABLE 2. RESULTS OF EXTRUSION TRIALS

Trial No.	Billet No.	Billet Material	Billet Temp°F	Billet Lubrication	Die Type	Die Temp°F	Container Temp°F	Die and Container Lub	Ram Speed in/mt (nominal)	Recorded Extrusion load, tons Max (Breakghrough)	Min	Product Surface Finish	REMARKS
Non Lubricated													
1	Al 1	Al 7075	750	None	Flat Face "O"	700	700	None	6.0	310	220	Excellent	
2	Al 2	"	"	"	"	"	"	"	"	370	210	"	
3	Al 3	"	"	"	Flat Face "T"	"	"	"	"	370	250	"	
4	Al 4	"	790	"	"	"	"	"	"	360	230	"	
Lubricated													
5	Al 5	"	750	Fel-Pro C300	Conical "O"	"	"	Fiske 604	80.0	180	160	Fair	Tearing on the Surface
6	Al 6	"	690	"	"	650	650	"	80.0	140	140	"	"
7	T1	Ti-6Al-4V	1725	0010 Glass	Conical "O" (I.D = 1.139 in)	750	750	"	"	250	200	Good	
8	T2	"	1725	"	Stream-lined "T"	750	800	"	"	280	220	Good	
9	S1	4340 Steel	2150	Polygraph	Conical "O" (I.D = 1.143 in)	750	800	"	"	200	160	"	
10	S2	"	"	"	Stream-lined "T"	"	"	"	"	200	175	"	
11	S3	"	"	"	"	"	"	"	"	230	180	"	
12	T3	Ti-6Al-4V	1690	0010 Glass	Stream-lined "T"	"	"	"	"	230	280	"	
13	Al 7	Al 7075	600 F	Fel-Pro C300	"	550	550	"	"	220	180	Fair	Tearing on the edge of the Tee
14	Al 8	Al 7075	"	"	"	"	"	"	"	180	180	Fair	Billet was partially extruded to study metal flow

Notes: (1) In Trial Nos. 7-13, graphite blocks were placed in between the billet and guide block, and complete billet was extruded through the die without leaving any butt.
(2) Billet Nos. S3 and Al 8 were gridded to study metal flow.
(3) After Trial No. 7, the conical die was lightly ground on the cone and I.D before pushing Billet No. 9.

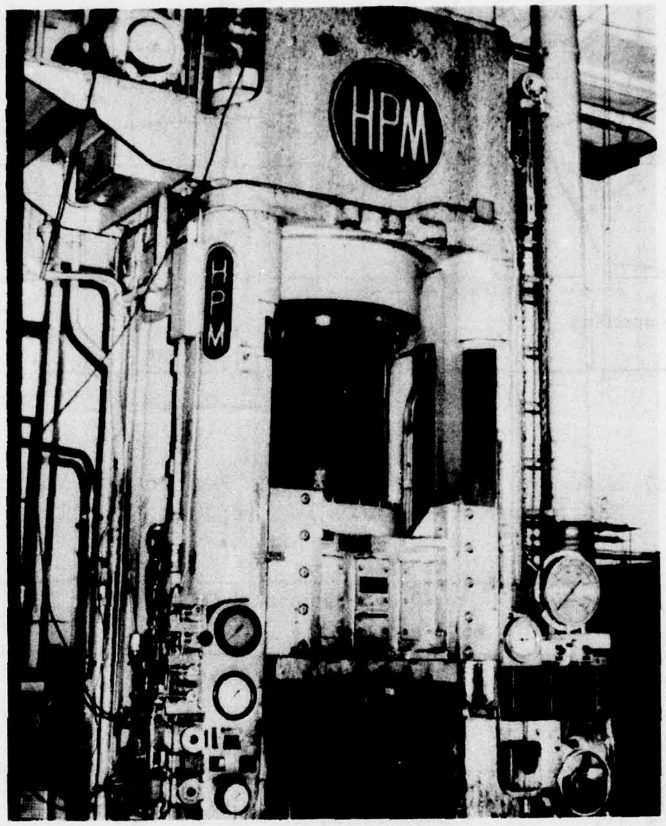
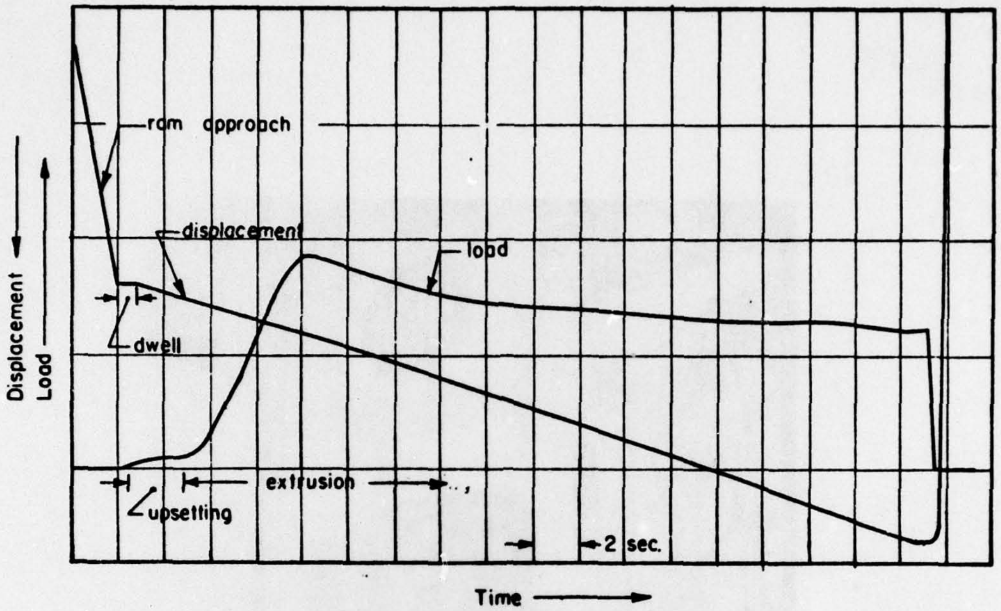
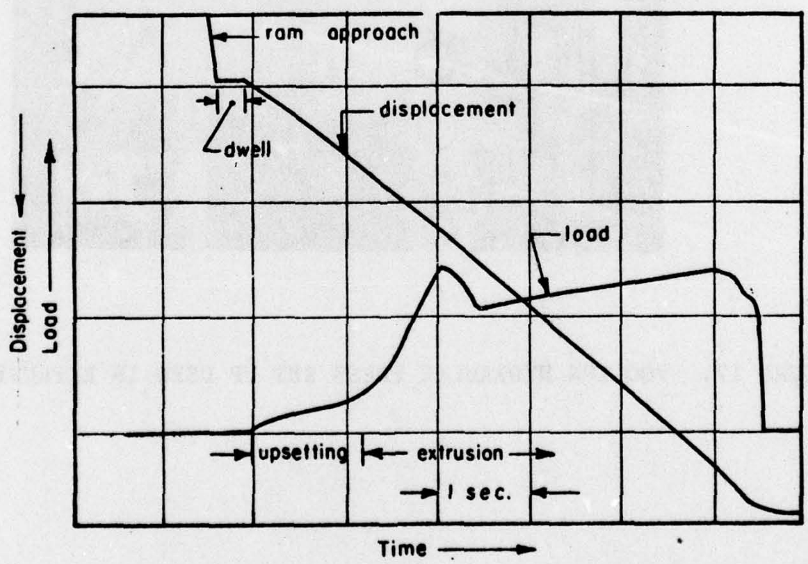


FIGURE 17. 700-TON HYDRAULIC PRESS SET UP USED IN EXTRUSION TRIALS



(a) Load Ram Displacement-Time Record for Nonlubricated Extrusion of Al 7075 Tee (Billet No. Al 3)



(b) Load Ram Displacement-Time Record for Lubricated Extrusion of Ti-6Al-4V Tee (Billet No. T2)

FIGURE 18. TYPICAL LOAD-RAM DISPLACEMENT RECORDS OBTAINED DURING THE EXTRUSION TRIALS

The results of extrusion trials are discussed separately for nonlubricated and lubricated extrusion trials.

Nonlubricated Extrusion

The main objective of conducting the nonlubricated extrusion trials was to check and validate the "ALEXTR" and "EXTCAM" computer systems for CAD/CAM of flat-face dies. These computer systems are evaluated by these trials in regard to the following capabilities:

- Usefulness in reducing die trials
- Capability to design and manufacture dies which give extrusions within specified tolerances
- Ability to predict extrusion loads.

Reduction in Die Trials

The scope of the project allowed only a limited number of trials. In the limited trials conducted, the high-strength aluminum alloy Al 7075 "Tees" were produced in the first set up. No modification was necessary or done to produce straight sections. Admittedly, the extruded "Tee" is a relatively simple shape. Nevertheless, these results show that the die layout and die bearing design performed by "ALEXTR" to balance the metal flow is essentially correct. The computer system is thus capable of designing dies to extrude straight sections of similar structural shapes without any major die modification.

Dimensions of the Extruded "Tees"

Table 3 gives (a) nominal dimensions of the "Tee", (b) dimensions of the die cavity determined by "ALEXTR" by taking into account the shrinkage, the stretch, the tongue deflection, and the cave allowances, (c) dimensions of the die cavity as manufactured, and (d) dimensions of the extruded "Tee" (before stretching) along the length. Comparing the manufactured die cavity dimensions with the designed cavity dimensions, it is seen that the two are almost identical with a difference less than .002 inch for any single dimension. This shows that an extrusion die can be manufactured to extremely close tolerances by the CAM techniques developed in this project.

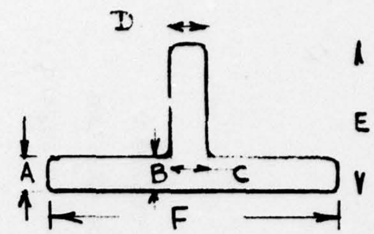


TABLE 3: DIMENSIONS OF THE EXTRUDED Al 7075 TEES

Part \ Dimensions	A	B	C	D	E	F
• Desired Product (Nominal Dimensions)	.188	.188	.188	.188	1.188	1.500
• Designed Die Cavity Dimensions	.190	.192	.195	.190		1.517
• Manufactured Die Cavity Dimensions	.191	.191	.195	.189	1.203	1.519
• Extruded Section Dimensions (before) Stretching at						
(a) 6" from front end - AL 3	.183	.183	.183	.181	1.186	1.502
AL 4	.1825	.183	.183	.180	1.184	1.501
(b) Middle of extruded section						
AL 3	.183	.183	.184	.181	1.1855	1.502
AL 4	.1825	.183	.183	.180	1.184	1.500
(c) 6" from trailing Edge						
AL 3	.183	.184	.183	.180	1.184	1.502
AL 4	.183	.183	.183	.179	1.182	1.502

As seen in Table 3, the dimensions of the extruded sections are within the allowed tolerances for extruded structural shapes[9]. The overall size (width and height) of the "Tee" section is within ± .004 inch of nominal dimensions, but the web thickness is undersize by .005 to .009 inch. The reason for this undersize thickness dimension is not obvious. The clearance between the die and the holder, the average length of the die land, and the nonuniform cooling of the section could influence these discrepancies in thickness dimensions. These results show that for a particular plant operation, the die design programs probably need to be "fine tuned" based on experience.

Prediction of Extrusion Loads

Using the measured loads for bar extrusions (Trials 1 and 2), the average flow stress, $\bar{\sigma}$, was back calculated using "ALEXTR". The input parameters used in these calculations were:

Section Area = 0.468 sq in.
Section Perimeter = 2.425 in.
Load = 310 tons for Al 1
= 370 tons for Al 2
Bearing Length = 3/16 inch
Billet Length = 6 inches
Container Diameter = 3.008 inches.

The following $\bar{\sigma}$ values were obtained from these calculations:

- For Al 1: $\bar{\sigma}$ = 9,224 psi
- For Al 2: $\bar{\sigma}$ = 11,010 psi

Using the mean value (σ = 10,117 psi), the load for "Tee" extrusion was predicted using "ALEXTR". Table below shows the predicted and measured loads.

Billet No.	Measured Load, Tons	Predicted Load, Tons
Al 3	370	368
AL 4	360	368

It is not surprising that the predicted loads are very close to the measured values. This technique of back-calculating flow stress using the theory and then using the calculated flow stress to predict loads under similar process conditions eliminates the errors introduced in characterizing temperatures, strains, strain rates, flow stress and frictional conditions. Essentially, the extrusion process is utilized as a test to measure flow stress. The limitation of the approach is that the obtained value of flow stress can only be used for extrusion operations which are conducted under conditions similar to those in the test.

Lubricated Extrusion

In the "SHAPE" system of computer programs, the design of the optimal streamlined die is based on the deformation model discussed in Chapter 1. In these trials, the model was evaluated by (a) comparing the observed metal flow with that assumed in the model, and (b) comparing the measured loads with theoretical predictions.

Metal Flow

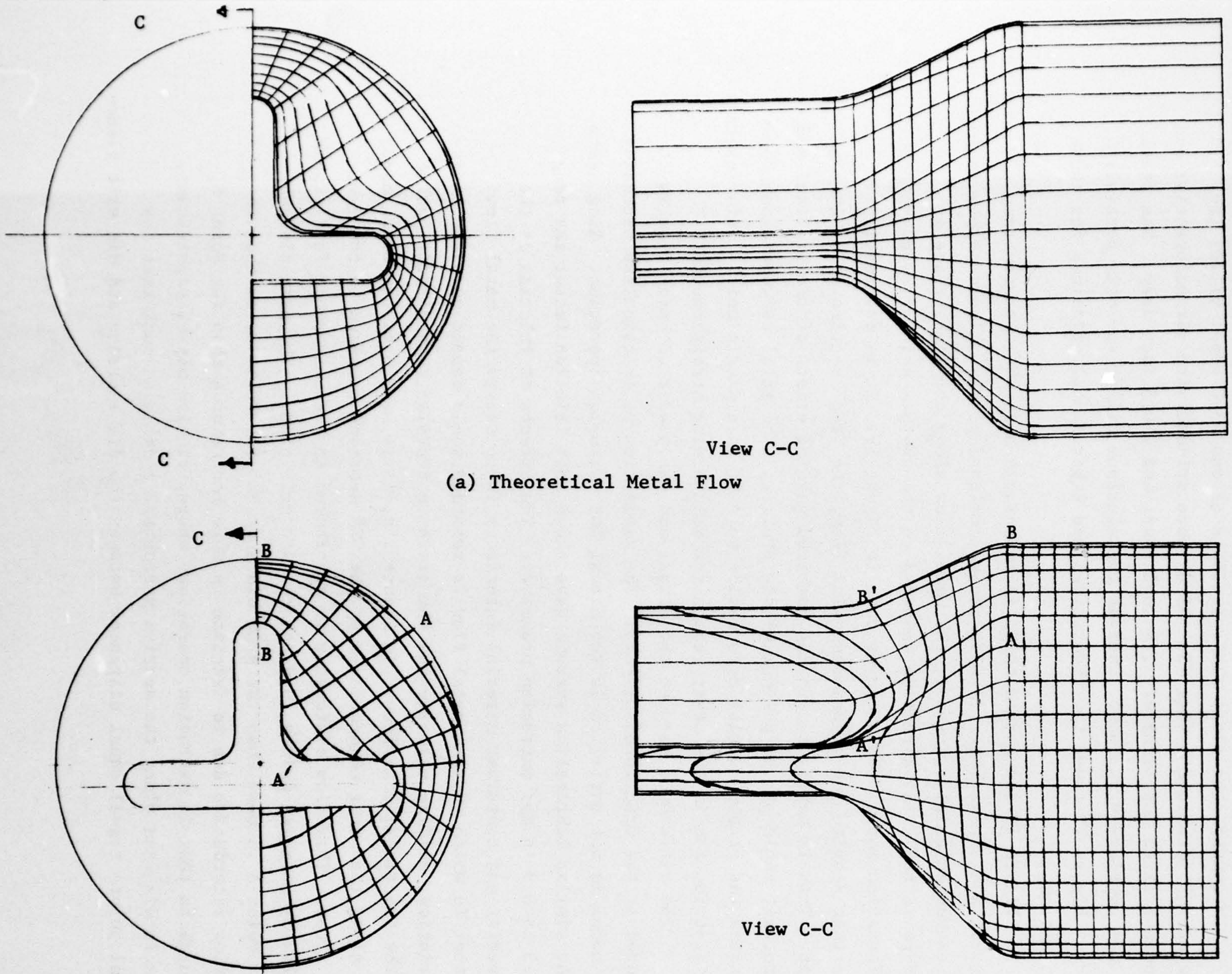
The surface profile of a streamlined die is determined by the geometric construction described in Chapter 1. The assumptions made in deriving the profile are (a) the billet undergoes deformation with minimum redundancy and friction, (b) there is a single neutral axis perpendicular to the cross-sectional plane at the die entrance, and (c) the flow lines along the die surface are such that their projections on a cross-sectional plane, say at die entrance, are straight-lines. These assumptions regarding metal flow are made to simplify the procedure for obtaining a streamlined profile. Using these assumptions and the criterion that the product should exit from the die without bending or twisting, the die profile is determined as discussed in Chapter 1.

A validating proof of the correct die design is that the product should come out straight. In the lubricated extrusion trials, all the extruded "T" sections were reasonably straight. No special guidance at the die exit was provided. Also, no die correction was necessary or made to extrude straight "T" sections.

To compare the metal flow, surfaces of one 4340 steel billet (No. S3) and one Al 7075 aluminum billet (No. Al 8) were gridded with circumferencial and longitudinal lines approximately 1/4 inch apart and 0.015 inch deep. The steel billet was completely extruded, whereas the aluminum billet was only partially extruded. Figure 19 shows the theoretical and experimental gridlines for these Al 7075 extrusion.

Figure 19 shows that there is reasonable agreement between the theoretical and actual metal flow in cross-sectional planes (planes perpendicular to the extrusion axis). However, the metal flow along the die surface is nonuniform in the axial direction compared to the uniform axial flow assumed in the deformation model. This can be seen in Figure 19. It is interesting to observe that despite the nonuniform axial flow, the "Tee" section still exited straight. This is partly due to the combined guiding effect of the die land and the zero exit angle of the polynomial die profile. The metal as a continuum body distributes the strains during deformation to exit as a single unit. This internal strain distribution is the other reason for maintaining straightness.

The difference between the actual and the predicted metal flow is attributed to the frictional effects. The assumption of frictionless extrusion in the model is not satisfied in the actual hot extrusion operation. Ring tests with the similar lubrication systems have shown that friction factor may range from 0.3 to 0.9 in hot extrusion processes. The effects of friction at the die material and container material interfaces is to retard the metal flow. The extent to which surface metal flow is retarded would depend upon the interface friction, sliding velocity and the distance traveled by a material point along the frictional interface. In Figure 19b, it is seen that the metal moved faster along the outer edge/corners of the "T" sections compared to the inner fillet areas. This flow difference is attributed to the difference in distance travelled by material points to reach the die exit plane. The path distance AA' for Point A is more than the path distance BB' for Point B, so that the metal-flow retardation due to friction is more for Point A than for Point B. This suggests that in extrusion operations where friction may be significant, a variable die land along the section periphery be designed such that the material points travel equal distances between the die entrance and die exit planes.



(a) Theoretical Metal Flow

(b) Actual Metal Flow

FIGURE 19. COMPARISON OF ACTUAL METAL FLOW WITH THAT PREDICTED FROM THEORETICAL DEFORMATION MODEL

Extrusion Loads

To determine the average flow stress for Ti-6Al-4V and 4340 steel, loads measured in rod extrusion trials (No. 7 and 9, Table 2) were used. The friction factors m_c and m_d for container and die surfaces, respectively, were taken to be 0.4 based on the results of ring tests given in Reference 8. The following values were obtained from the load analysis programs of "SHAPE":

- Ti-6Al-4V: $\bar{\sigma}_{avg}$ = 13,520 psi
- 4340 steel: $\bar{\sigma}_{avg}$ = 10,815 psi

Using these values and $m_c = m_d = 0.4$, the load predicted for the "Tee" sections are given below, along with the measured values.

Billet No.	Billet Material	Measured Load, Tons	Predicted Load, Tons
T2	Ti-6Al-4V	280	244
S2	4340 Steel	200	195
S3	4340 Steel	230	195

The agreement between loads is reasonable with predicted values slightly lower than the measured values.

Effect of Product Shape on Extrusion Load

Comparing the extrusion loads for rod sections with those for "Tee" sections (see Table 2), it is seen that the shape influences the load only slightly. This observation agrees with the results of extrusion trials conducted with round, rectangle and "T" shapes[14]. In the present trials, the extrusion loads for "T" sections are slightly higher than those for round sections under similar process conditions. This agrees with the theoretical and actual results of the Phase-I study[1]. From theoretical analysis, it was predicted that the increase in redundant deformation is small with a change of shape from round to elliptic sections of increasing aspect ratio (ratio of major axis to minor axis). The increase in the extrusion pressure is due mainly to the increase in die surface area. In lubricated extrusion, low friction reduces the effect of an increase in surface area. These results show that the extrusion loads for relatively simple, nonsymmetric sections can be estimated assuming a circular cross section with an area equal to that of the nonsymmetric section.

Lubricated Extrusion of Al 7075

Conventionally, Al 7075 is extruded without lubrication using flat-face dies. In nonlubricated extrusion, temperature rises locally in the deforming billet due to plastic deformation and internal shearing. To keep the temperature below incipient melting, the exit speed is kept low (less than 7 fpm). With lubricated extrusion, higher speeds should be possible as the temperature increased due to shearing being eliminated.

In Trials Nos. 5, 6, 13 and 14, (Table 2), round and "T" sections of Al 7075 were extruded using conical and streamlined dies and the lubricated process. These trials were conducted at exit speeds of 46 fpm, approximately 5 times the maximum conventional speed. Surface tearing was observed. This is attributed to inadequate lubrication and too high an exit speed. Die pick up during extrusion was noticed when the billets were not extruded completely through the die. Lowering the temperature did not eliminate the tearing. Further trials with reduced speeds and other lubrication systems were not conducted as these were beyond the scope of the project. These trials, however, show that for lubricated extrusion of Al 7075 to be successful, further work on suitable lubricants and process conditions is required.

CONCLUSIONS

From the results of the extrusion trials, the following conclusions are drawn:

Nonlubricated Extrusion

(1) "ALEXTR" and "EXTCAM" systems of computer programs for design and manufacture of flat-face dies can be applied successfully to the extrusion of high-strength aluminum alloy structural shapes, such as "T".

(2) NC programs for machining the flat-face die and EDM electrode are correct and adequate for structural sections. This was demonstrated by the flat-face "T" die fabricated to desired dimensions by NC milling and EDM using tapes generated from "EXTCAM".

(3) The flat-face dies designed and manufactured using CAD/CAM techniques developed in this program gave straight "T" sections without any die modification. The computer technique thus have the potential of reducing die trials in extrusion of structural shapes.

(4) The extruded "T" sections were straight and within dimensional tolerances. This shows that the various design aspects, such as die layouts, die-land variation, thermal and stretcher shrinkage, etc., are correctly formulated in the "ALEXTR" system. Further "Tuning" to give better dimensional tolerances can be done by incorporating experience based modifications in "ALEXTR".

(5) The extrusion loads can be predicted accurately provided accurate flow stress data is used. Rod extrusion can be used as a test to provide this information.

Lubricated Extrusion

(1) Streamlined dies for lubricated extrusion of simple structural shapes of titanium and steel can be designed and manufactured using the "SHAPE" system of computer programs.

(2) The NC programs are adequate for machining three-dimensional streamlined surfaces (die or electrode) providing a smooth transition from round to structural sections. This was demonstrated by machining the EDM electrode for a streamlined "T" section.

(3) Straight "T" sections of titanium and steel sections were extruded through a streamlined die without any die modification. Thus, with "SHAPE", die designs which would result in straight extrusions can be obtained for simple structural shapes.

(4) With "SHAPE", extrusion loads can be predicted with reasonable accuracy, provided accurate flow stress and friction data are available.

(5) In the extrusion of simple structural shapes, the product shape does not significantly influence the extrusion load.

(6) Further development work on suitable lubricants and process conditions is needed to make lubricated extrusion of aluminum alloys a viable process.

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V. Nagpal, C. F. Billhardt and T. Altan
Battelle's Columbus Laboratories
Columbus, Ohio 43201

Technical Report - January 1978

102 pages, illustrations, tables, Contract DAAG46-76-0054
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Final Report, July 19, 1976, to October 18, 1977

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Titanium Alloys
Steel

The overall objective of this program was to develop practical computer-aided design and manufacturing (CAD/CAM) techniques for extrusion of aluminum alloys, steels, and titanium alloys. This program was conducted in two phases. This report covers the Phase-II work, which was completed by performing the following major tasks: (a) assemble geometric modules to represent practical extrusion shapes, (b) apply the CAD/CAM method to a streamlined die, (c) develop a CAD/CAM system for non-lubricated extrusion through flat-face dies, (d) conduct extrusion trials and evaluate CAD/CAM extrusion results, and (e) evaluate the economics of CAD/CAM in extrusion. In order to enhance readability, the results of Phase-II work are presented in the form of two volumes. Volume I includes the following chapters: (1) CAD/CAM of Streamlined Dies for Lubricated Extrusion of "T" Sections, (2) CAD/CAM of Flat-Face Dies for Nonlubricated Extrusion of Aluminum Structural Shapes, and (3) Extrusion of "T" Sections of Aluminum, Titanium and Steel using computer-aided techniques. Volume II is the Instruction Manual and describes the content and use of computer programs.

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